# Lecture 4: Folds

# Outline

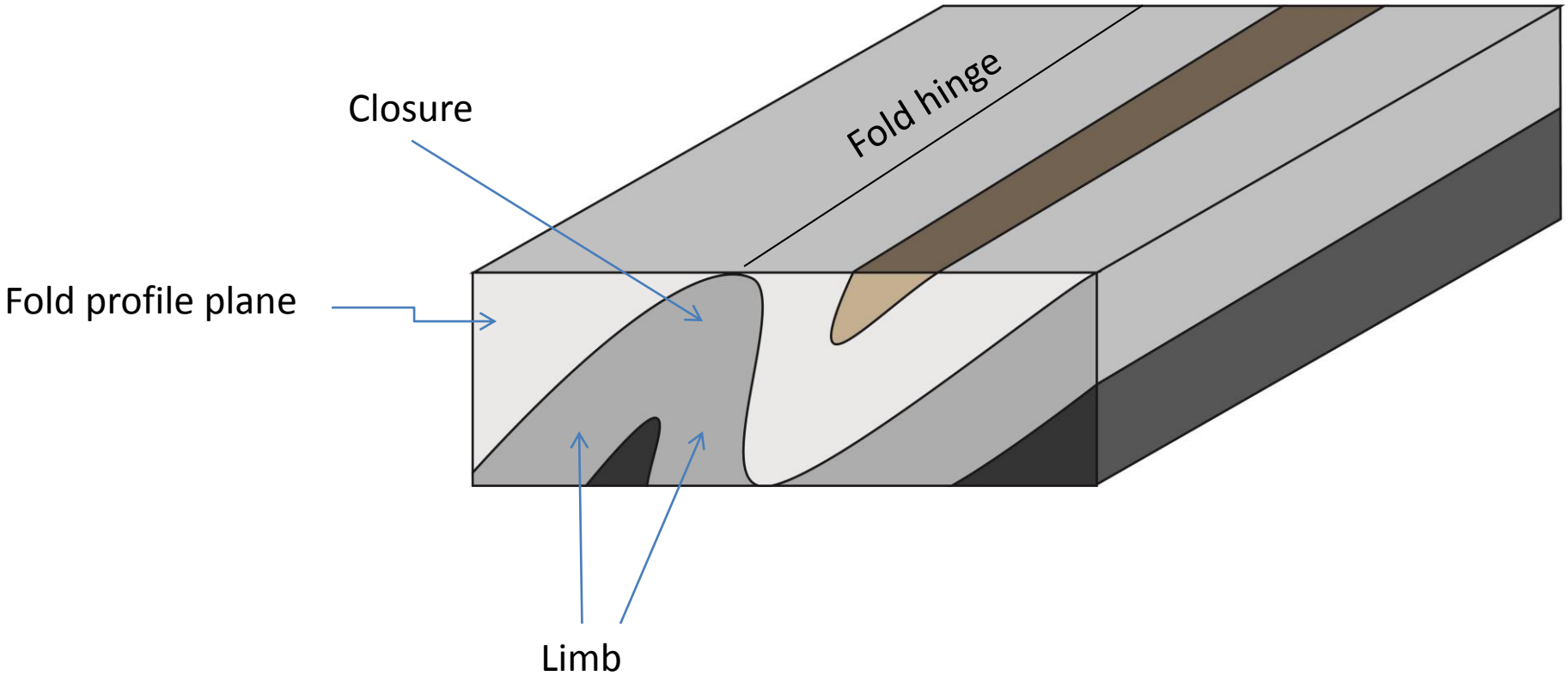
- Part I: Review of folds chapter in basic structural geology
  - Basic concepts
  - Fold overprinting, generation and time

- Part II: fold analysis
  - Correlation: one example
  - Analysis using equal-area projection: one example

# Part I

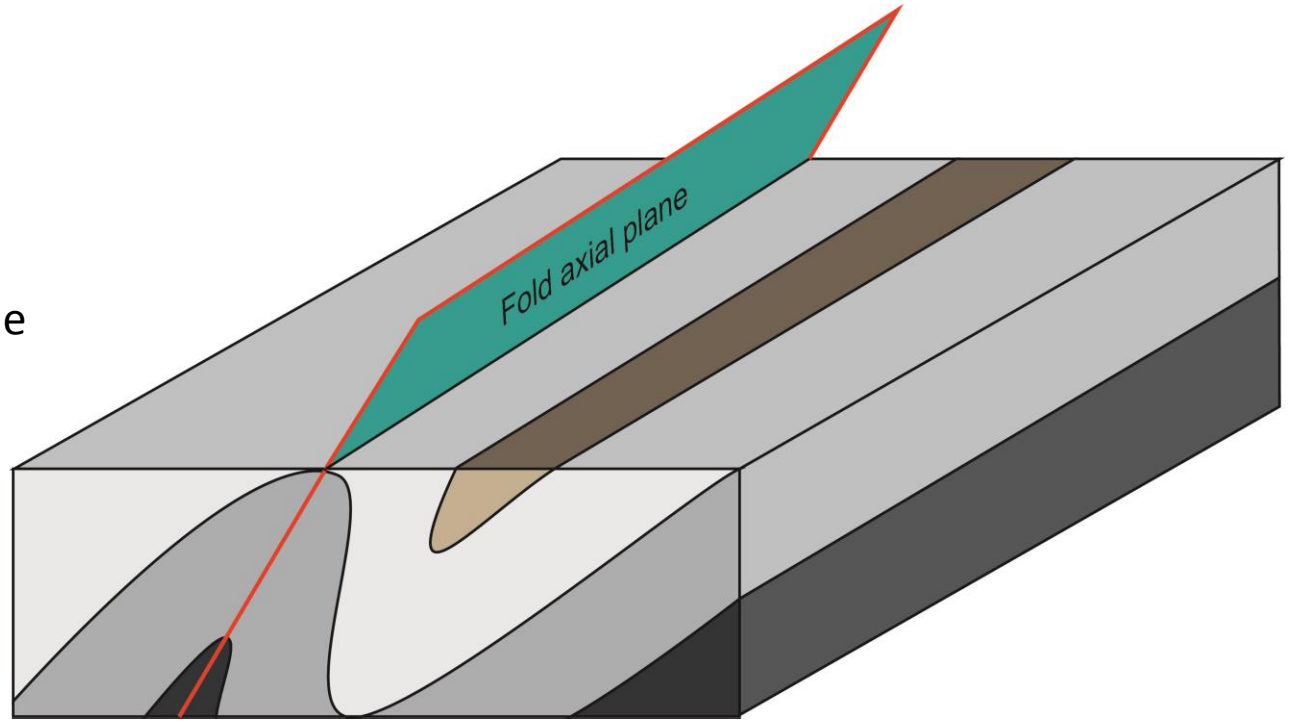
# Review

# Basic concepts



# Basic concepts

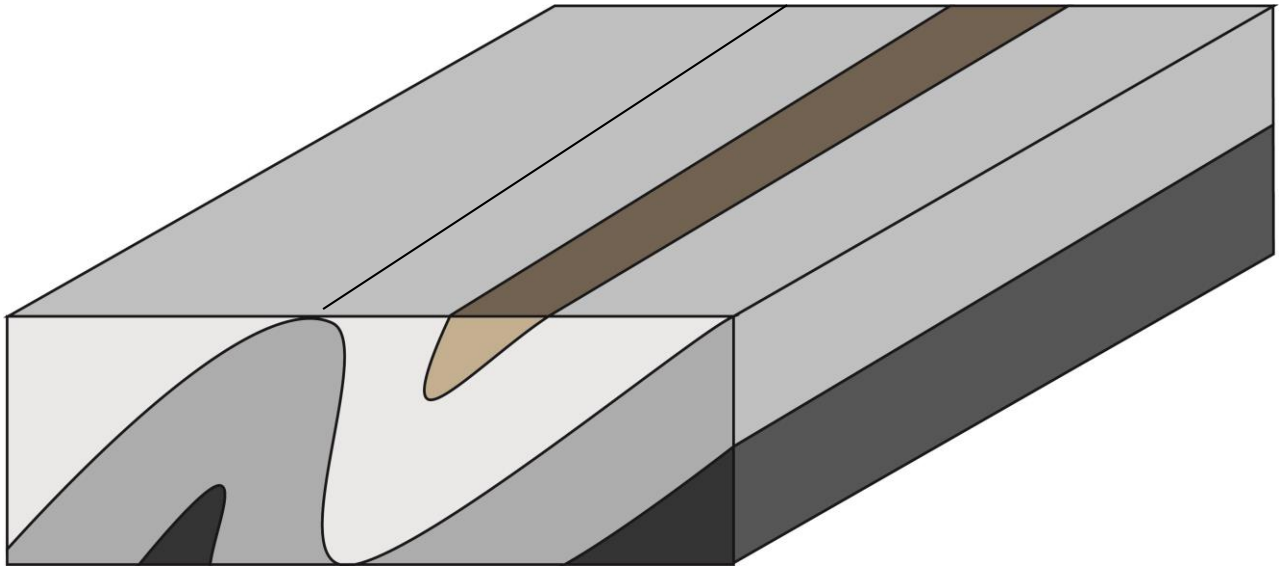
Axial surface
If planar, it is an axial plane



# Antiform or Anticline

"U-shaped"

"∩-shaped"

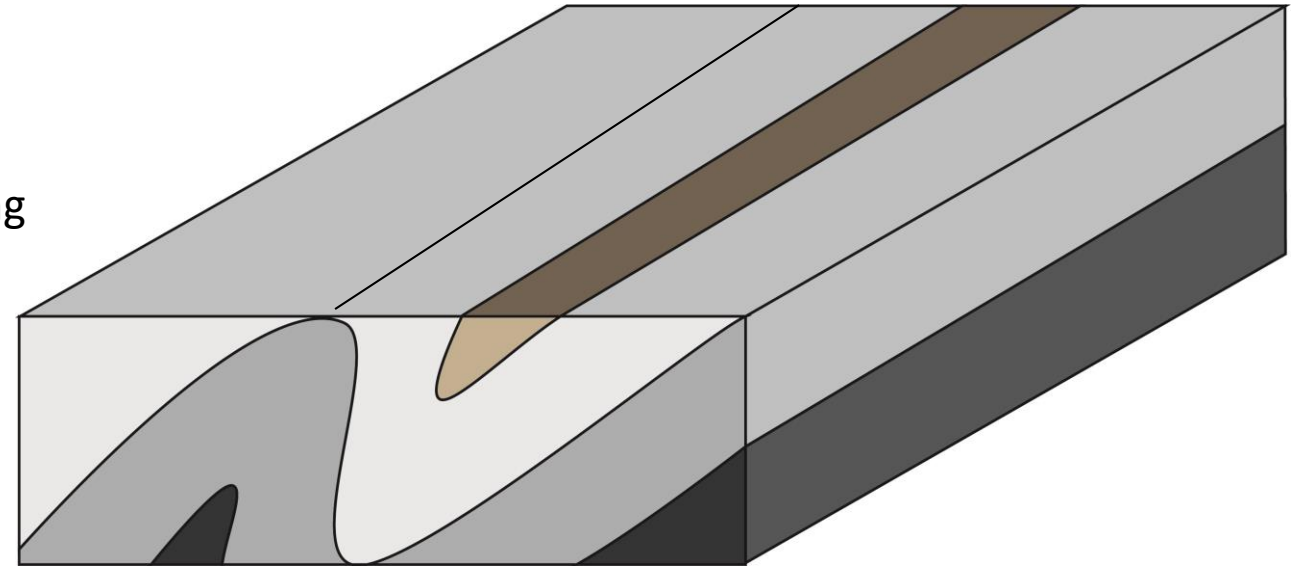


Anticline?

# Antiform vs Anticline

Synform: “U-shaped”

Antiform: “∩-shaped”

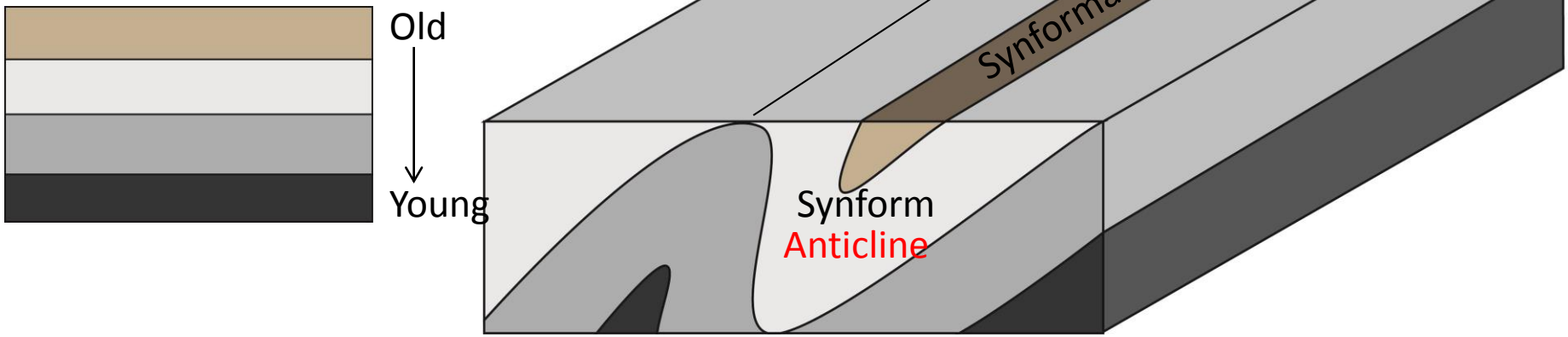



Anticline: old at core
Syncline: Young at core

# Antiform vs Anticline

Synform: “U-shaped”

Antiform: “∩-shaped”




Anticline: old at core
Syncline: Young at core

Antiform
Syncline

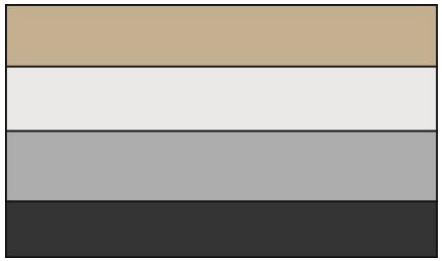
Antiformal syncline

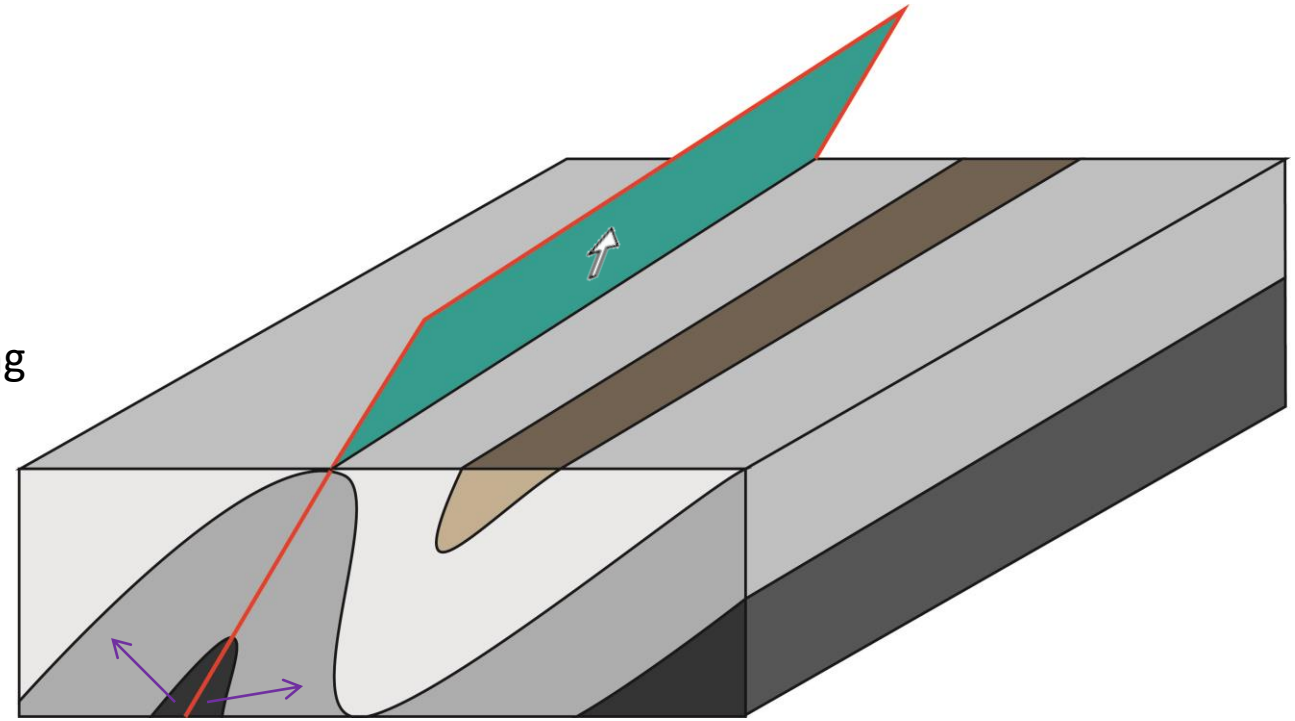
Overturned beds: either antiformal syncline or synformal anticline

# Younging dirction and Fold facing

Synform: “U-shaped”

Antiform: “∩-shaped”

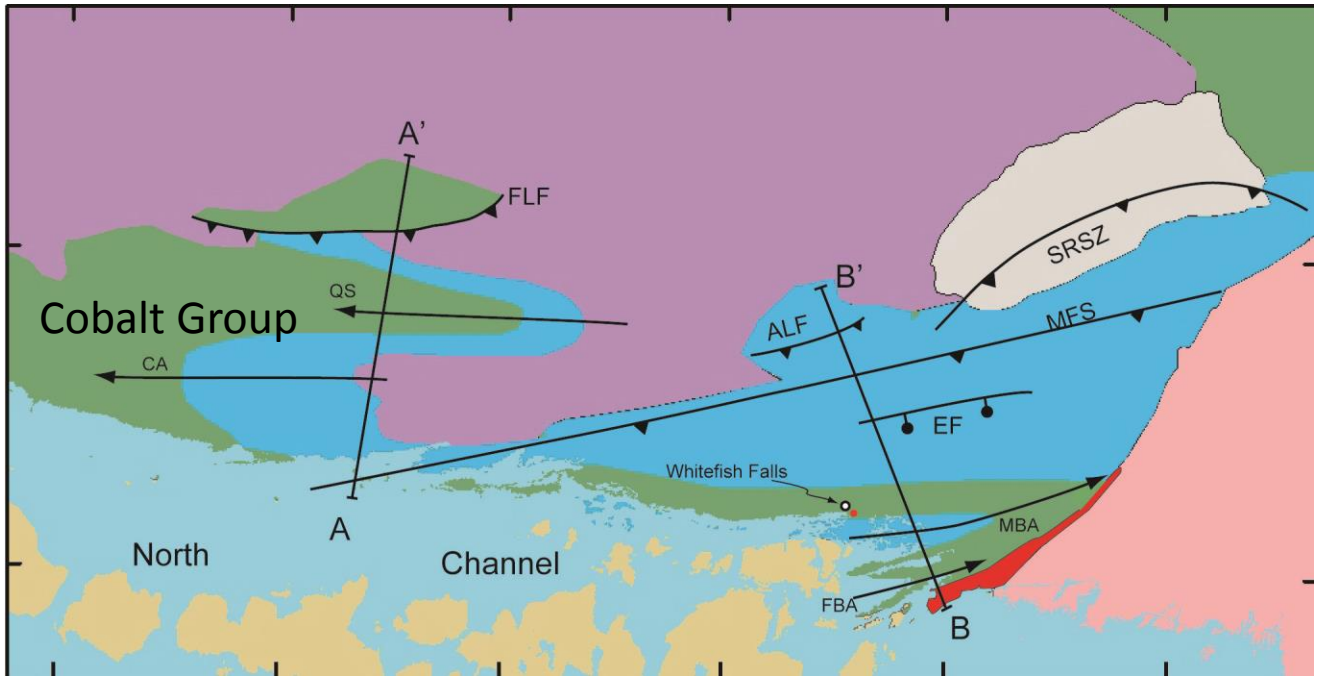


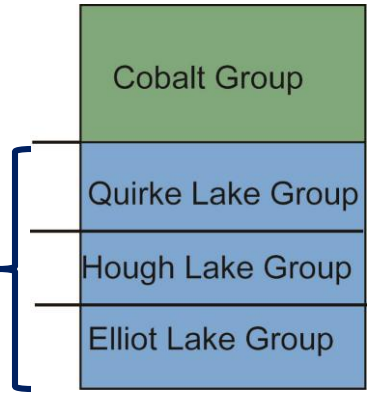
Anticline: old at core
Syncline: Young at core

Opposite younging directions

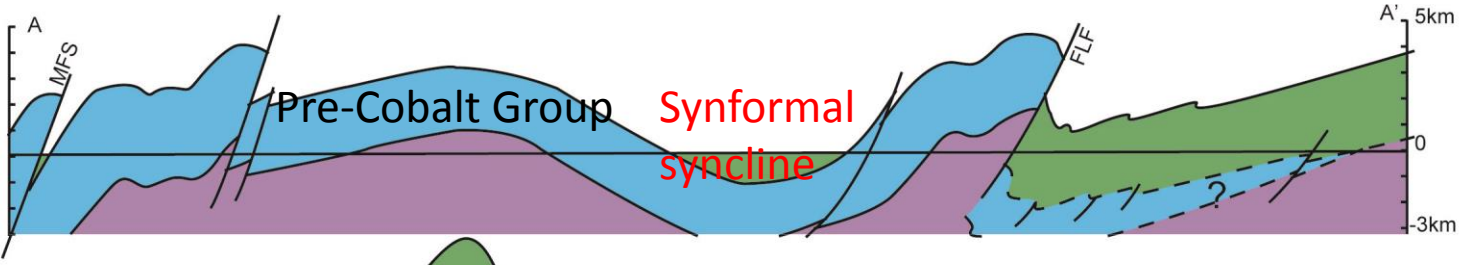
Fold facing: direction of younging in the plane of axial plane

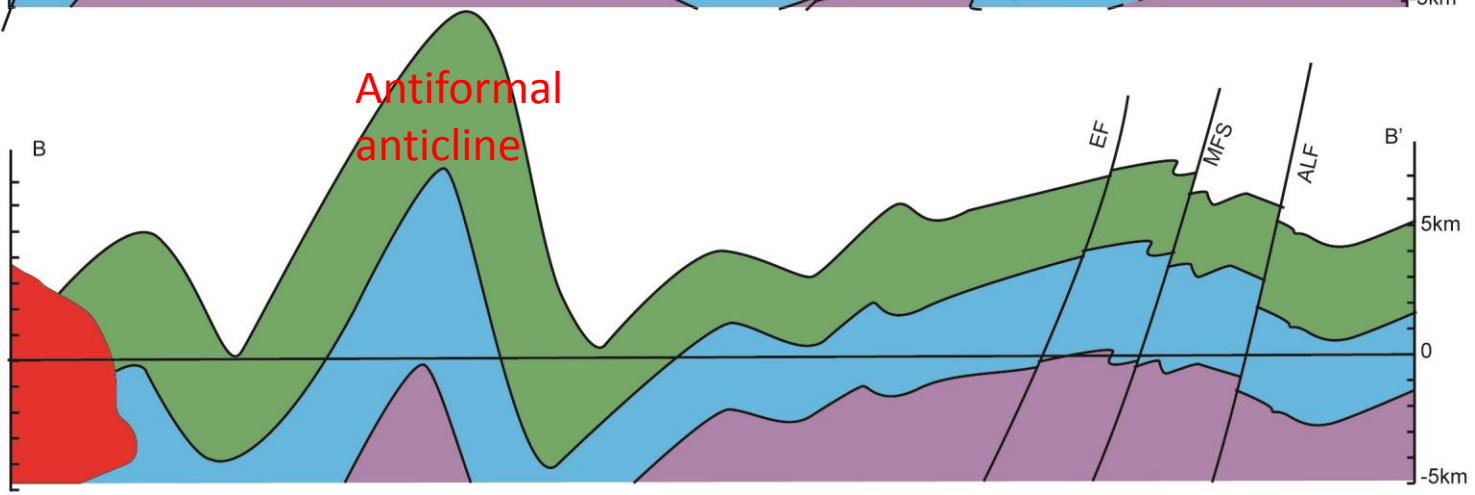



Huronian Supergroup

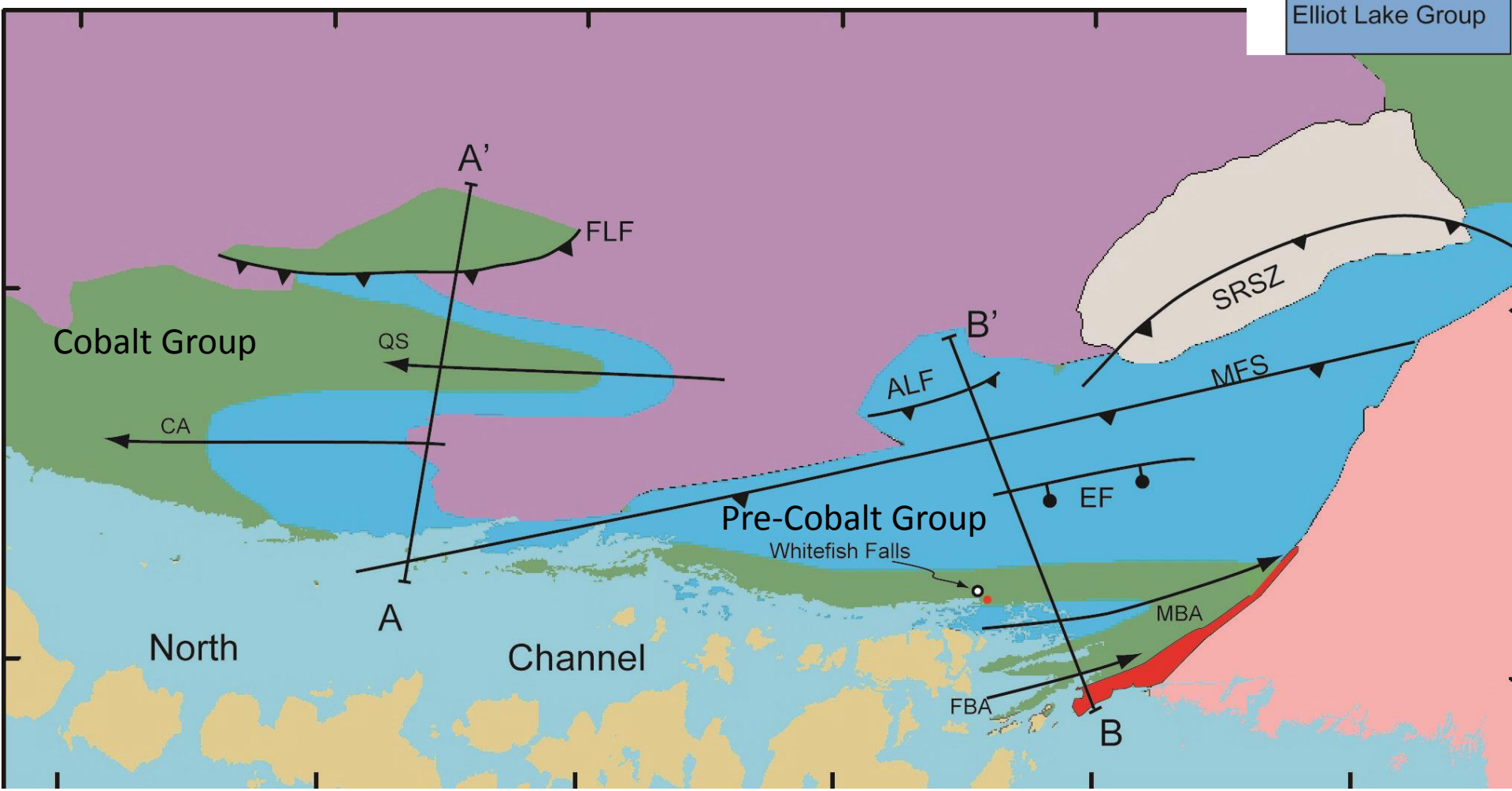



Pre-Cobalt Group



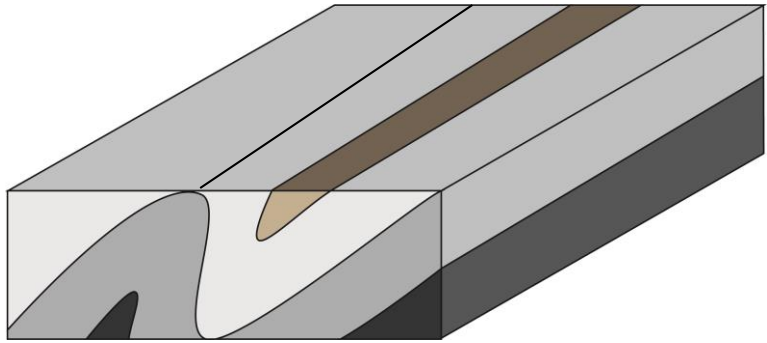
# Fold facing


Huronian Supergroup
Cobalt Group
Quirke Lake Group
Hough Lake Group
Elliot Lake Group
A'
FLF
Cobalt Group
QS
CA
B'
SRSZ
ALF
MFS
EF
Pre-Cobalt Group
Whitefish Falls
A
North
Channel
MBA
FBA
B

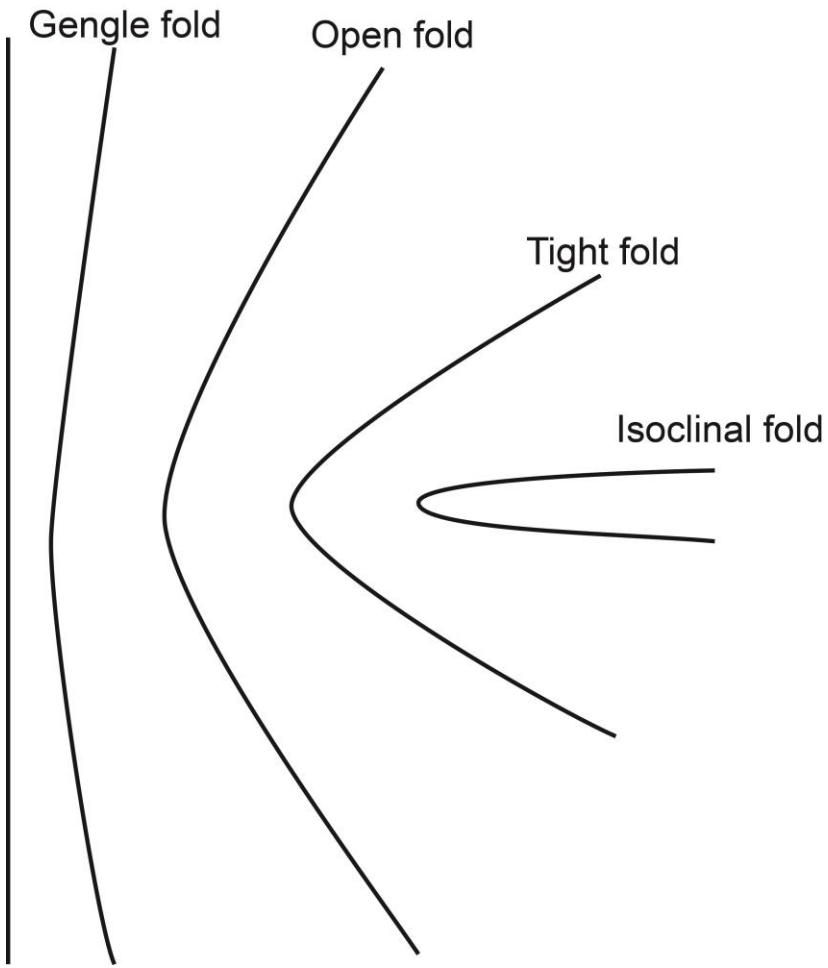
# Fold style

The geometrical characteristics of a fold on the profile plane define its style.

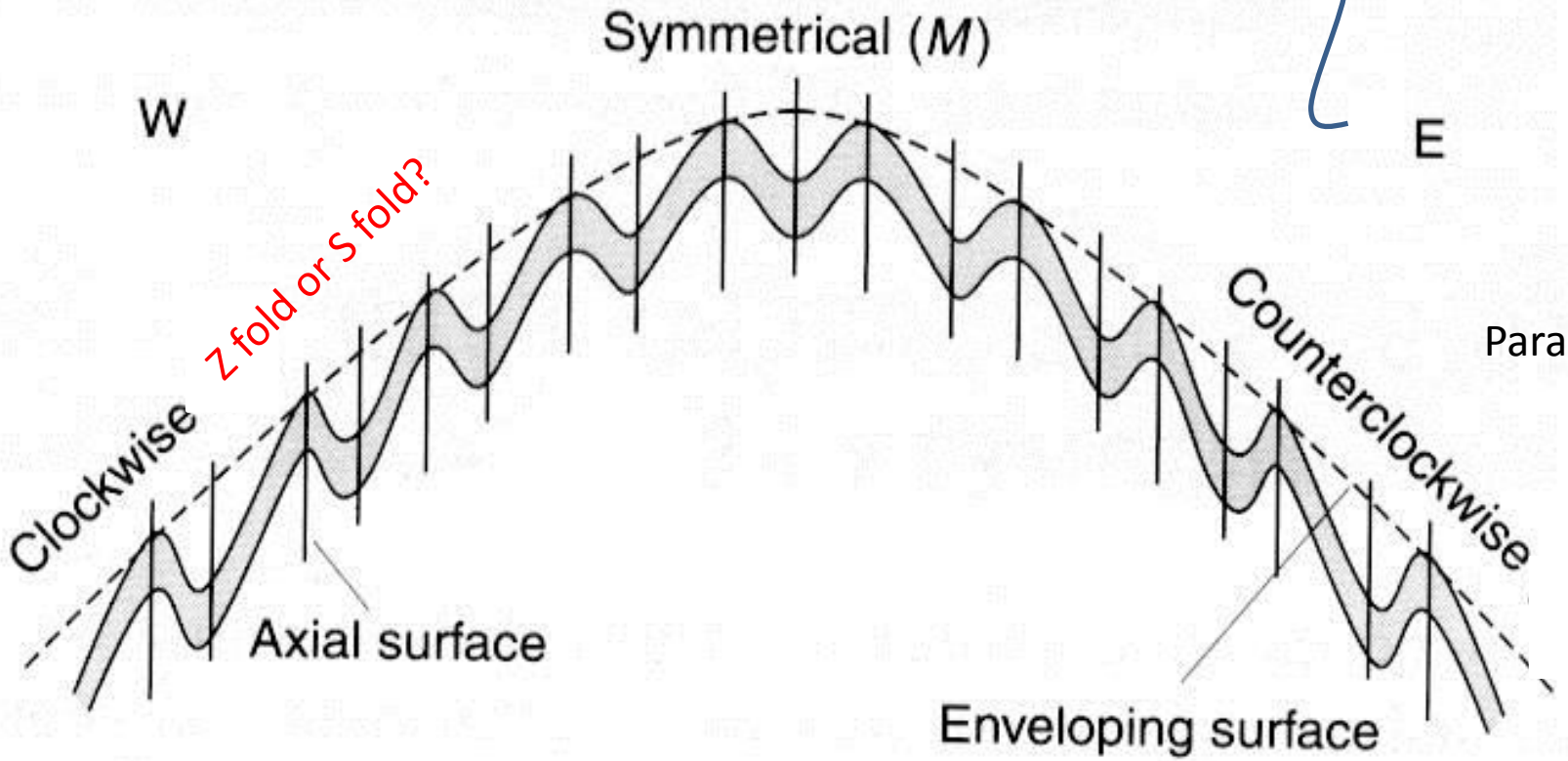
- Inter-limb angle (tightness of a fold)
- Symmetry (s-, z-, or m-fold)
- Curvature distribution (round curved or sharp V-shaped
- Axial surface trace
- Harmony



# Inter-limb angle



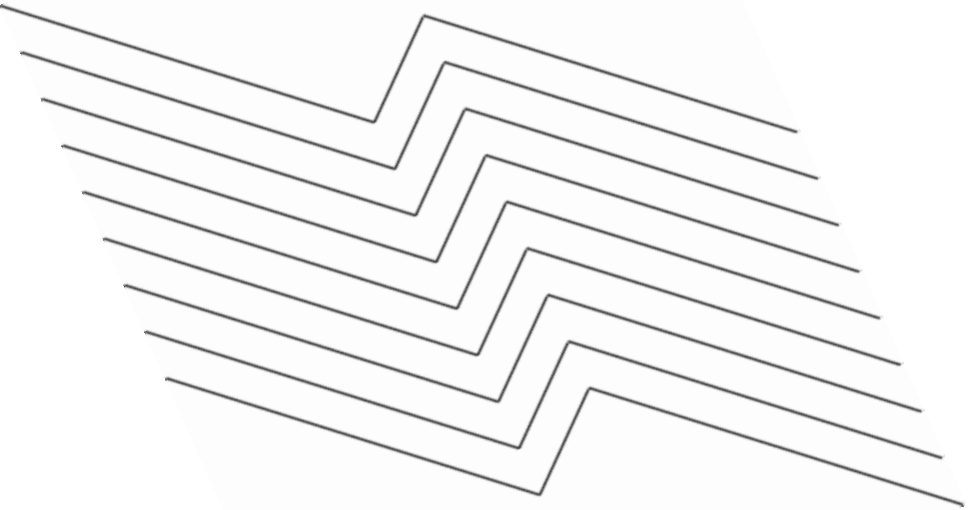
# Asymmetry



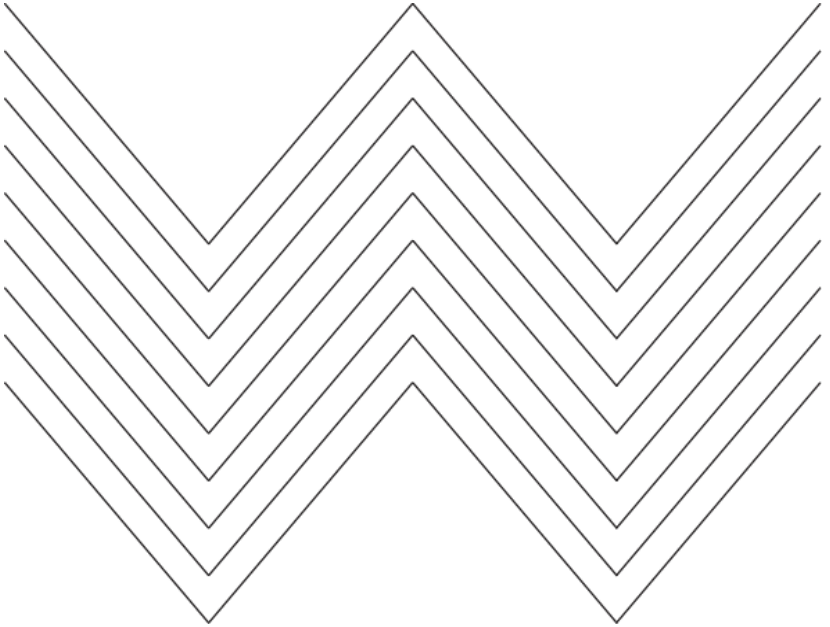

Parasitic fold

Long limb-short limb-long limb

Looking down plunge

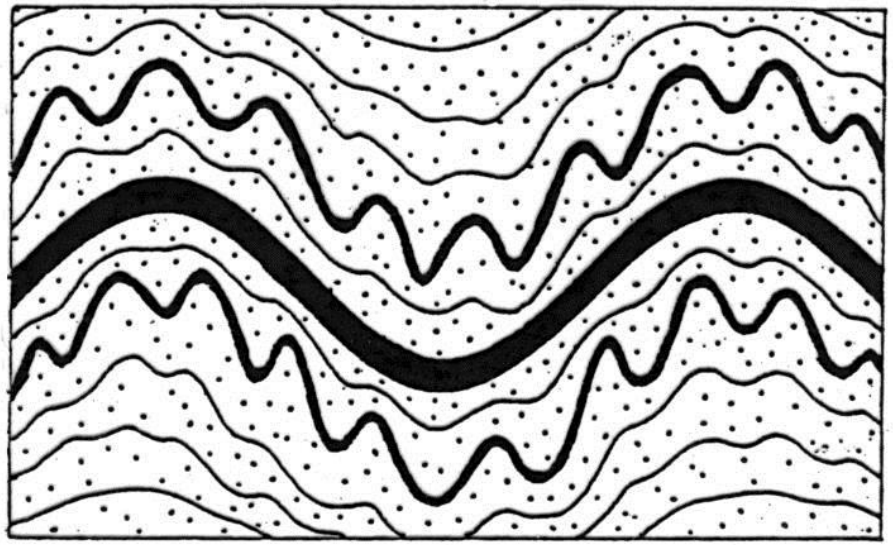


Kink fold



Chevron fold

Folded multilayer
Harmonic fold
Disharmonic fold

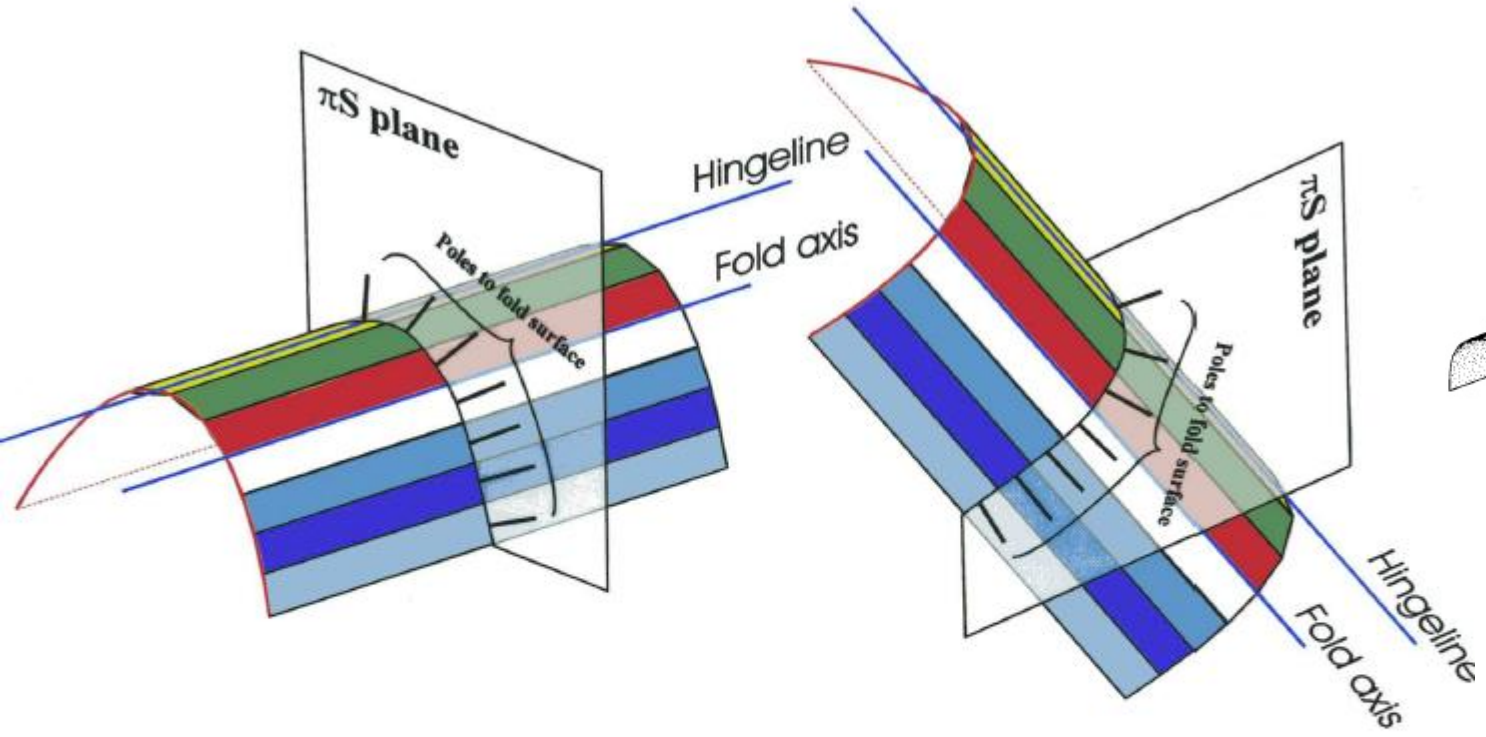


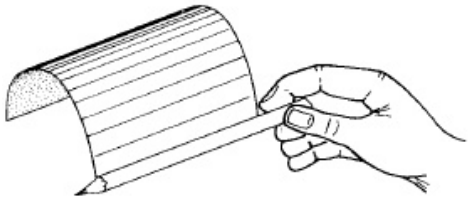
# Fold style

Inter-limb angle: tightness
Rounded or angular?

# Fold classifications

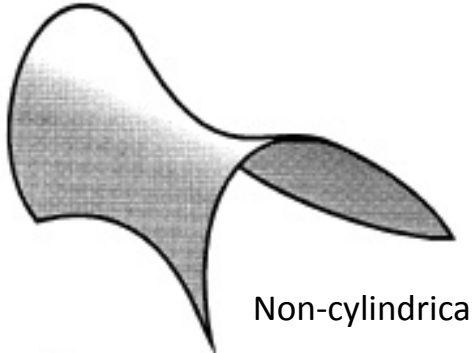
# Fold classification: cylindrical fold and Non-cylindrical fold



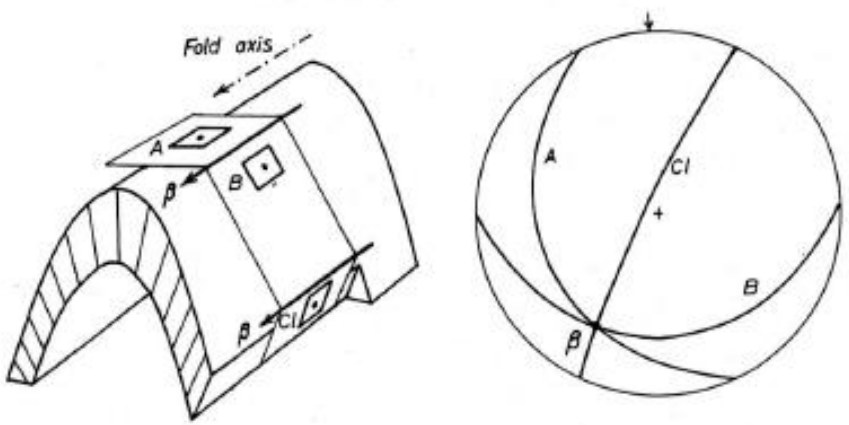
cylindrical fold

**For a cylindrical fold, the poles to the fold surface lie in a common plane (πS) perpendicular to the fold hingeline.**



Non-cylindrical fold

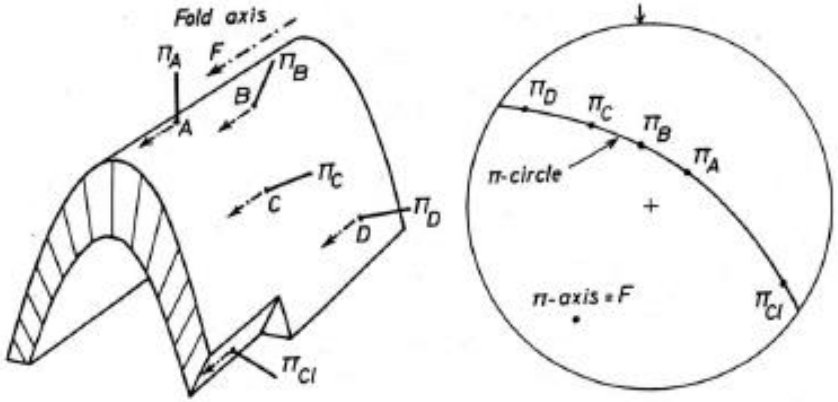
# $\beta$ and $\pi$ diagrams

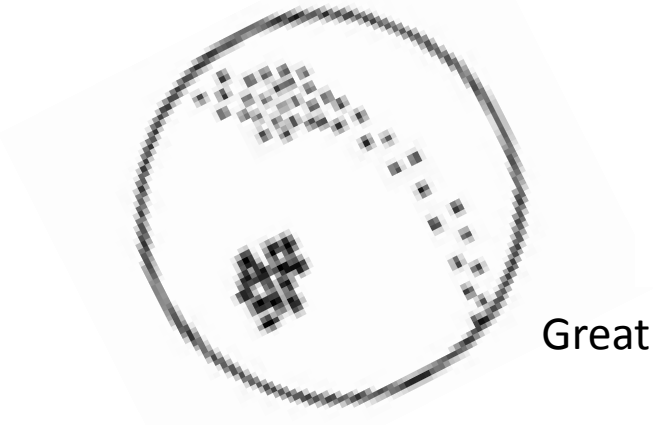



## For a perfect cylindrical fold:

**Fold surface dips plotted as great circles intersect at a single point, which is the hinge line plot ( $\beta$ -diagram).**

**Fold surface dips plotted as plane poles lie in a great circle, the pole to which is the hinge line plot ($\pi$-diagram).**

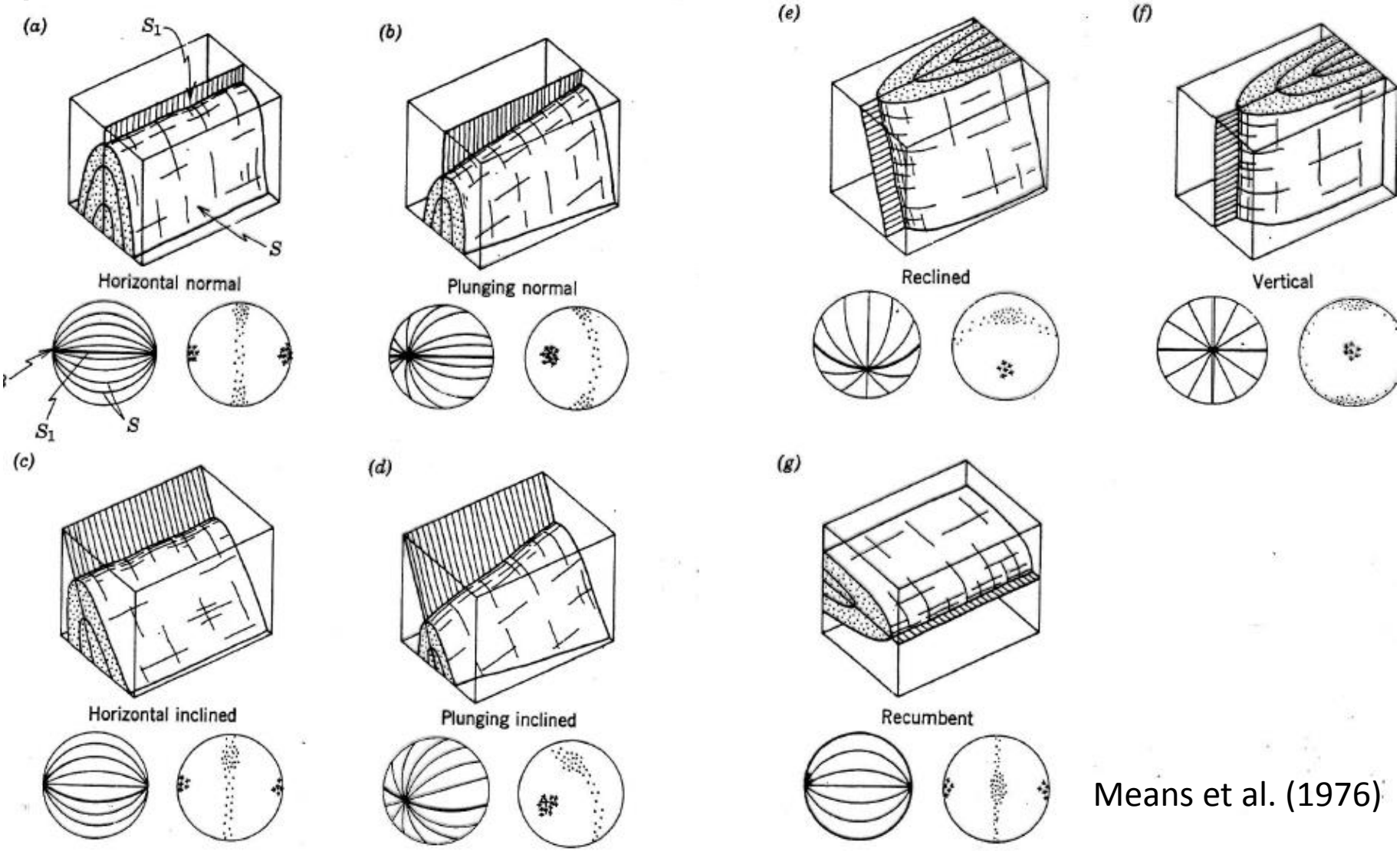


Great circle girdle

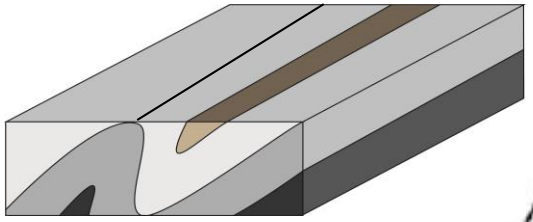
# Fold classification based on orientation

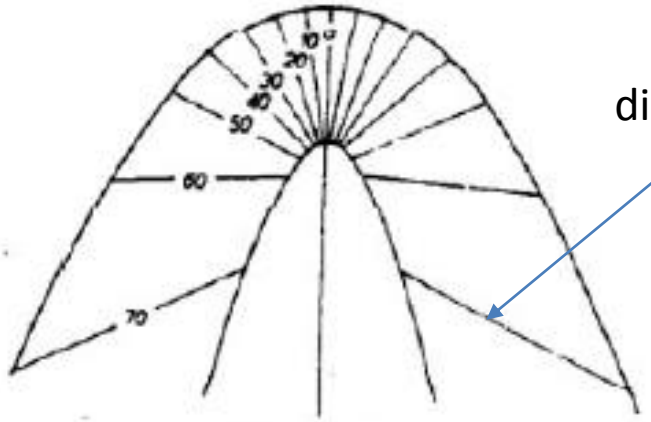
## $\beta$ and $\pi$ diagrams



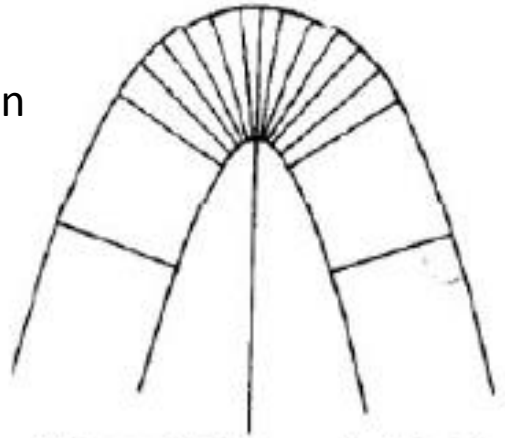

Means et al. (1976)

# Fold classification

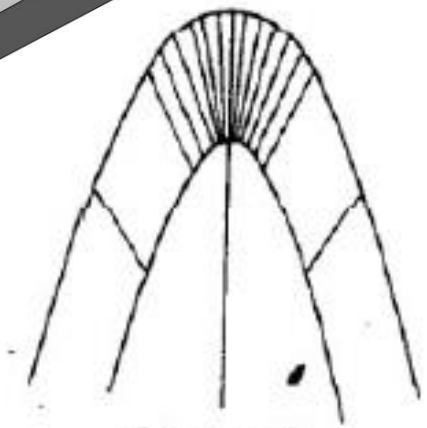




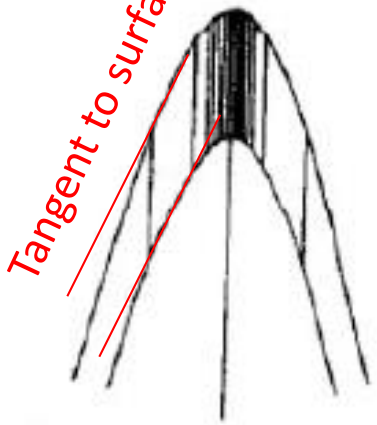

Class 1A



Class 1B: Parallel fold



Class 1C




Class 2: Similar fold

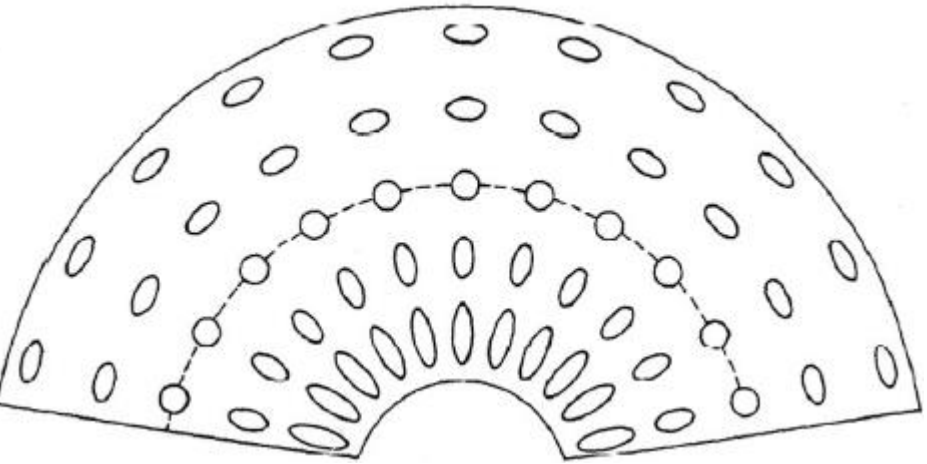
Class 3

Ramsey's classification

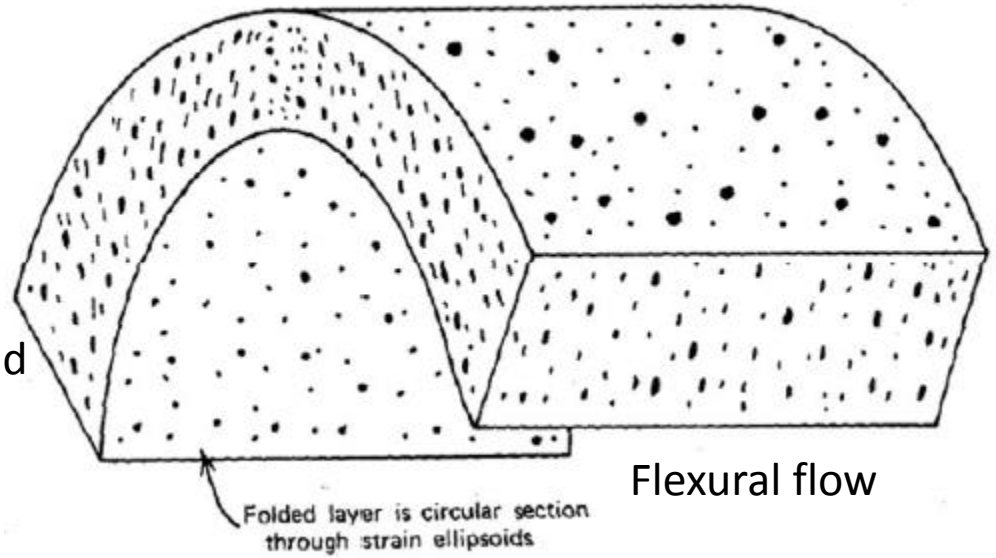
Means et al. (1976)

# Classic models for fold formation

Orthogonal flexure

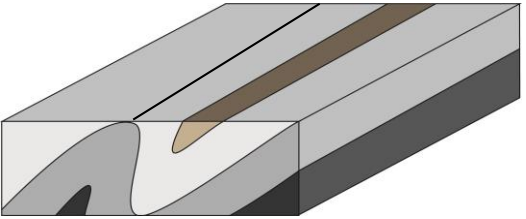


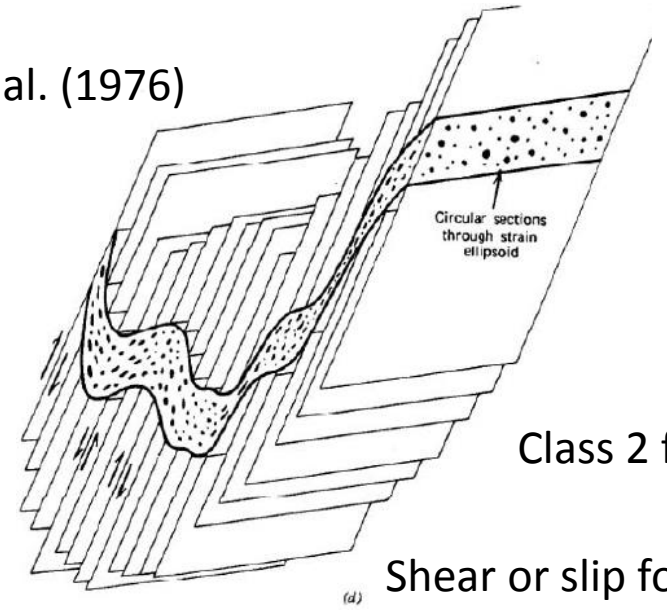
Class 1B fold




Flexural flow

Means et al. (1976)

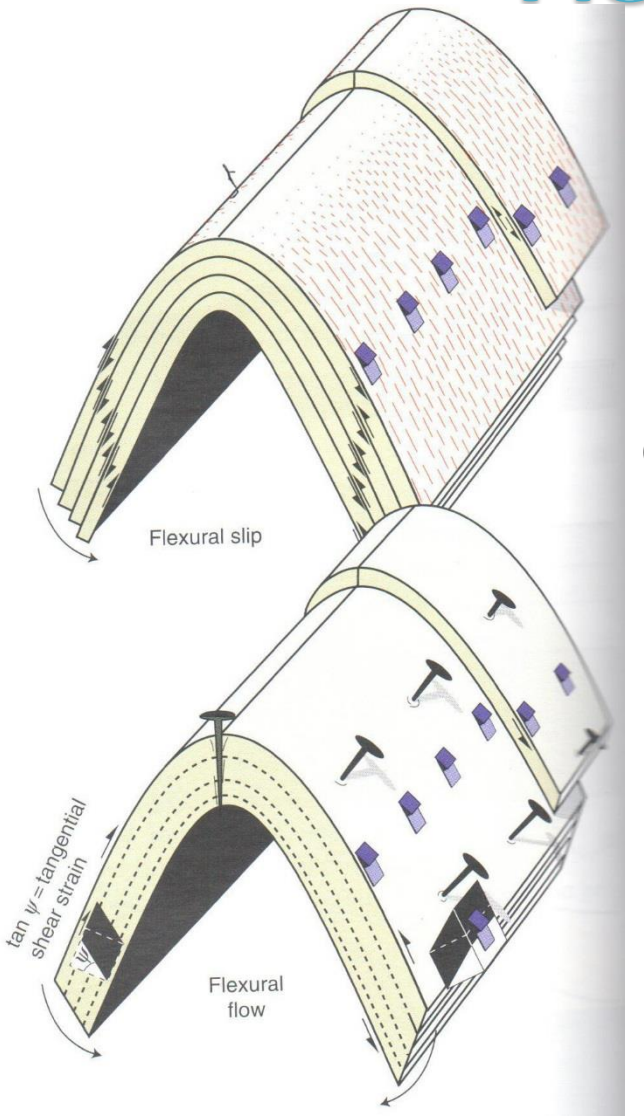





Class 2 fold

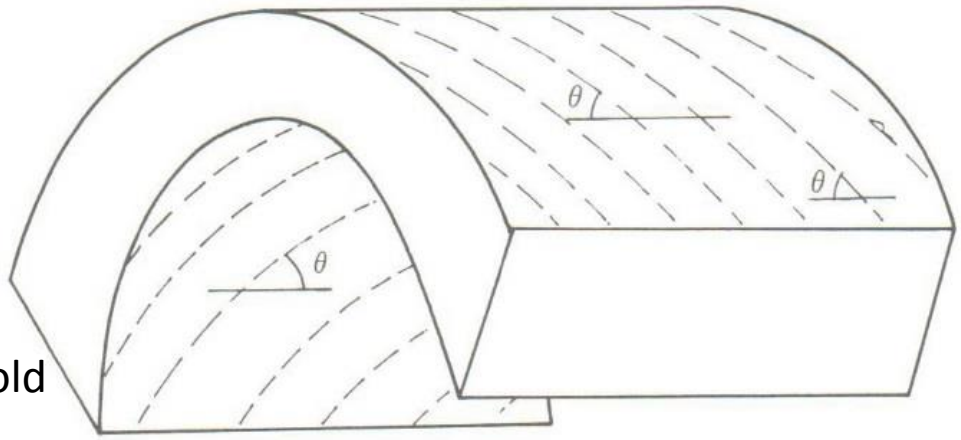
Shear or slip folding

# Flexural slip/flow




Fossen (2010)

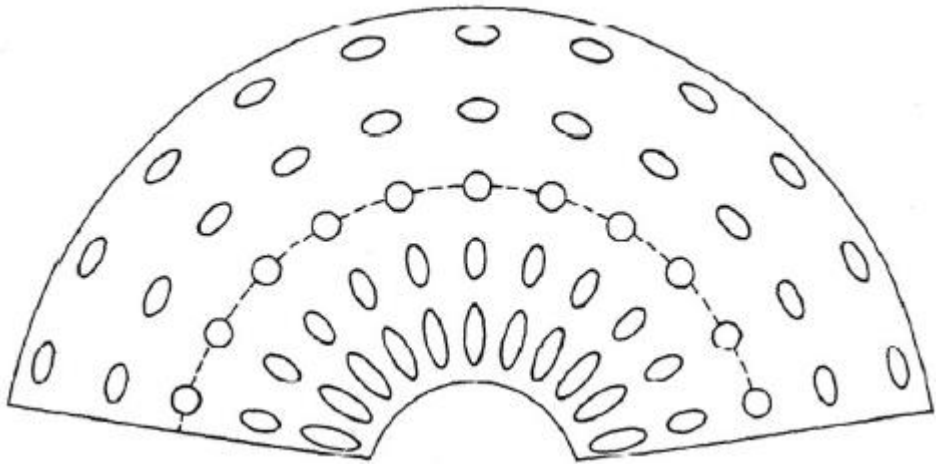
Class 1B fold




Means et al. (1976)

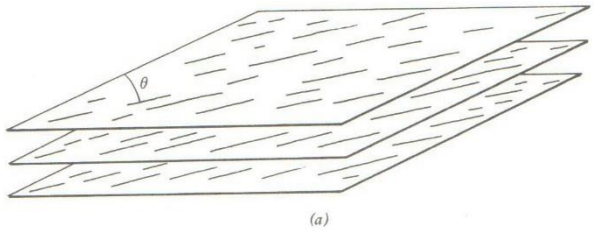
Stereographic projection of lineation? Pattern?

# Orthogonal flexure

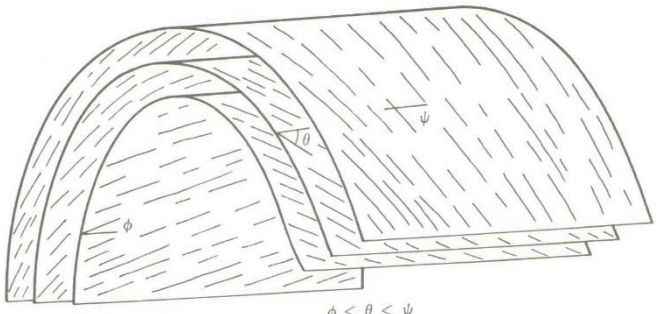


Means et al. (1976)

- All lines orthogonal to the layer, remain…
- Class 1B
- Neutral surface



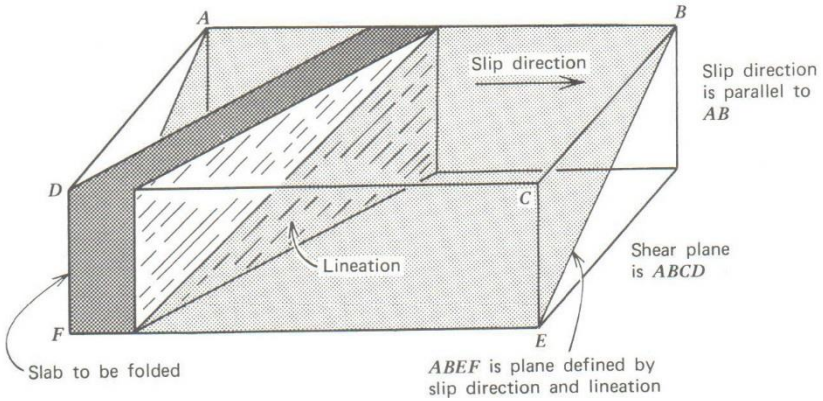

(a)



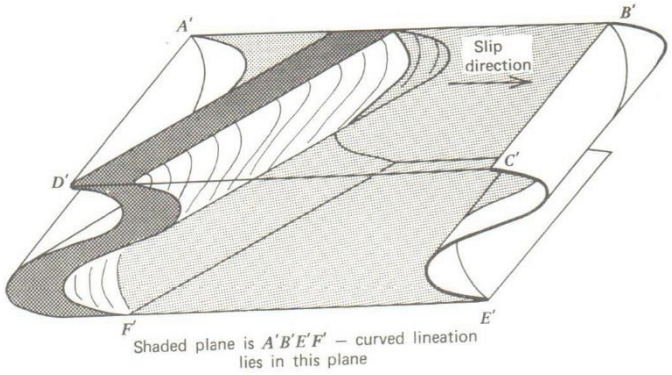

$\phi < \theta < \psi$

Stereographic projection of lineation? Pattern?

# Passive folding




Stereographic projection of lineation? Pattern?

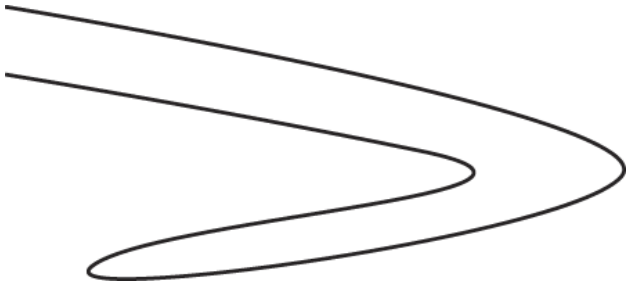



Means et al. (1976)

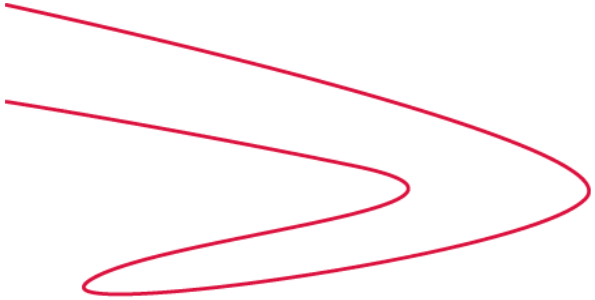
Class 2 fold

# Fold generation and timing

At place A:

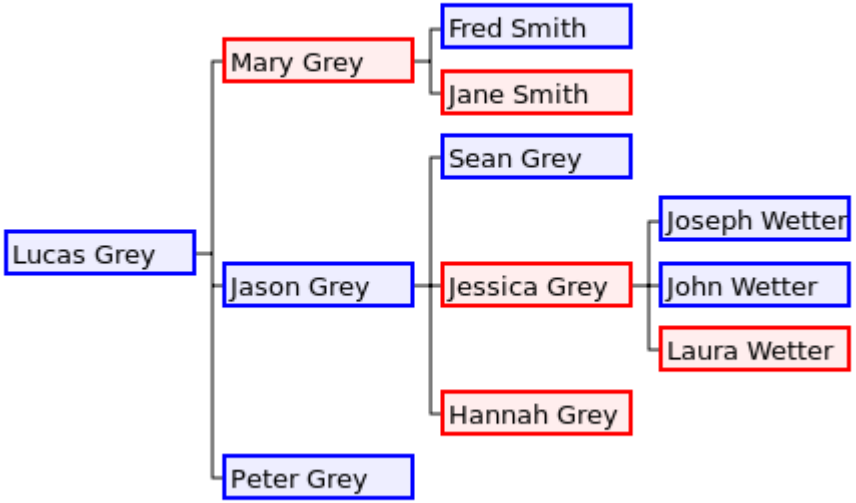


Several meters away at place B:



Is $F_1$ at place B older than $F_2$ at place A?

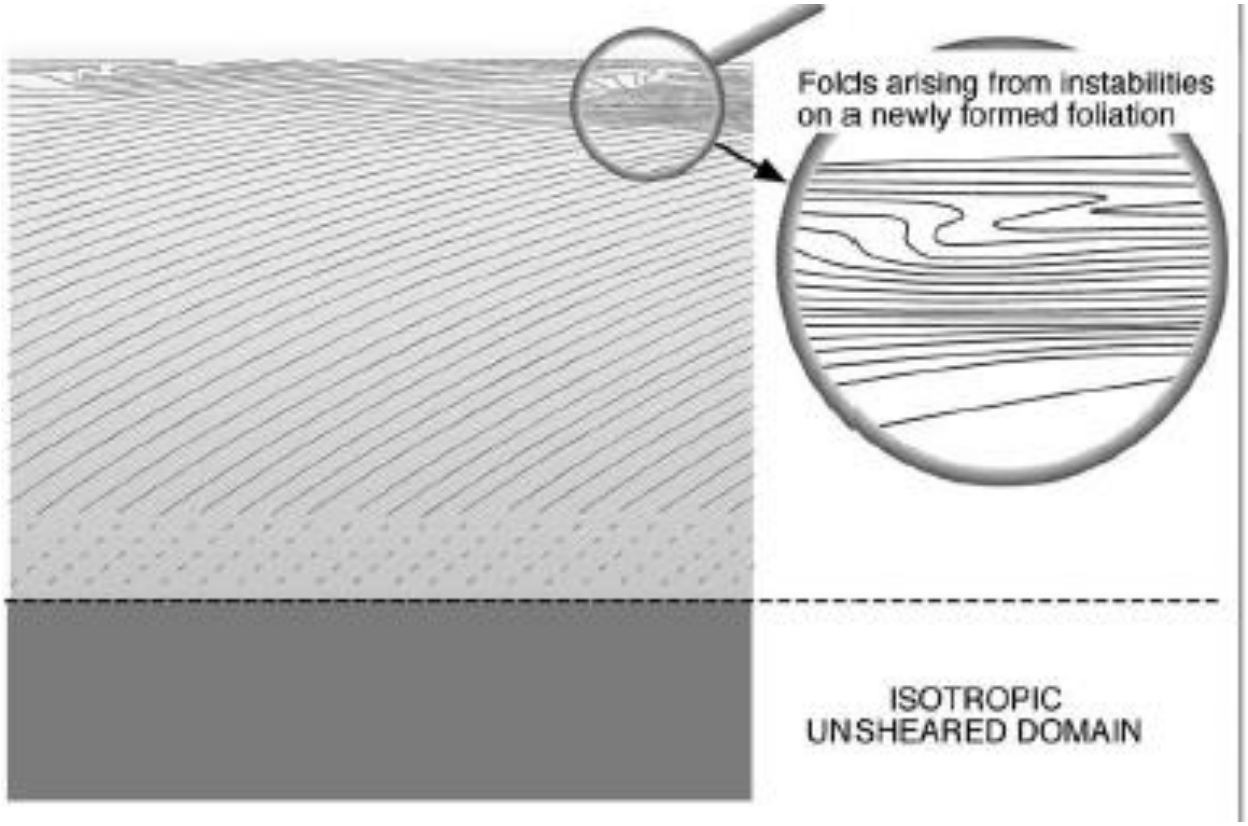
Family tree




From internet

Is Mary older than Jessica?
Is Laura necessarily younger than Jane?

# Folds in shear zones

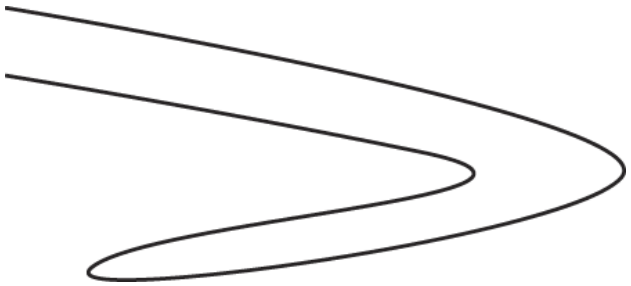



Carreras (2005)

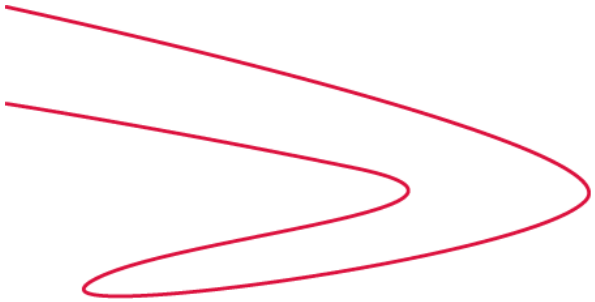
Several generations of folds can develop in one progressive deformation phase.

# Fold generation and timing

At place A:



Several meters away at place B:



Not necessarily true if $F_1$ and $F_2$ developed in one progressive deformation.
It is older if $F_1$ and $F_2$ developed in two discrete deformation phases.

Is $F_1$ at place B older than $F_2$ at place A?

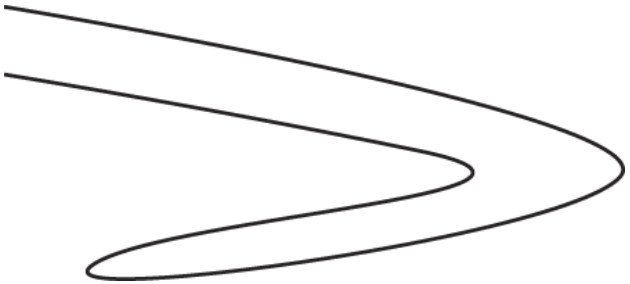
# Part II

# Fold Analysis

# Fold correlation

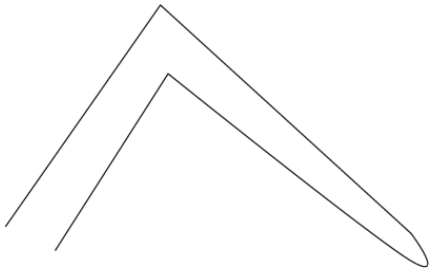
Outcrops are generally discontinuous, isolated.

Outcrop A



Two generations: $F_1$ and $F_2$

Outcrop B



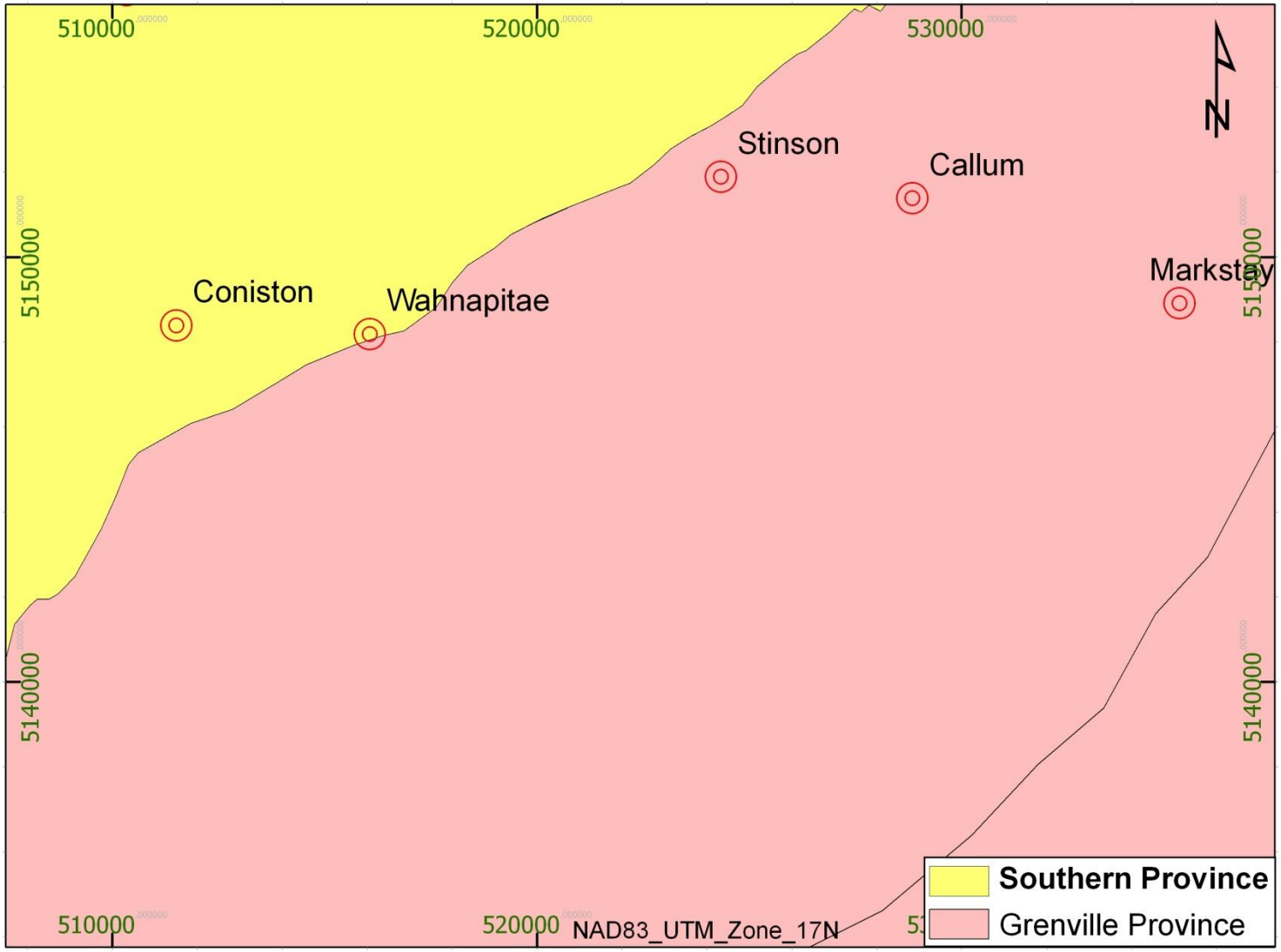
$F_1$ and $F_2$? $F_2$ and $F_3$? Or $F_1$ and $F_3$?

Style; orientation; Overprinting relationship

Be careful if try to correlate folds  outside of shear zones with those in shear zones

# One example

# Study area


510000
520000
530000
N
Stinson
Callum
Markstay
Coniston
Wahnapitae
5150000
5140000
Southern Province
Grenville Province
NAD83_UTM_Zone_17N

# Folds

Style?

Orientation with respect to the foliation?


Style?

Orientation?

Overprinting?

Generation?

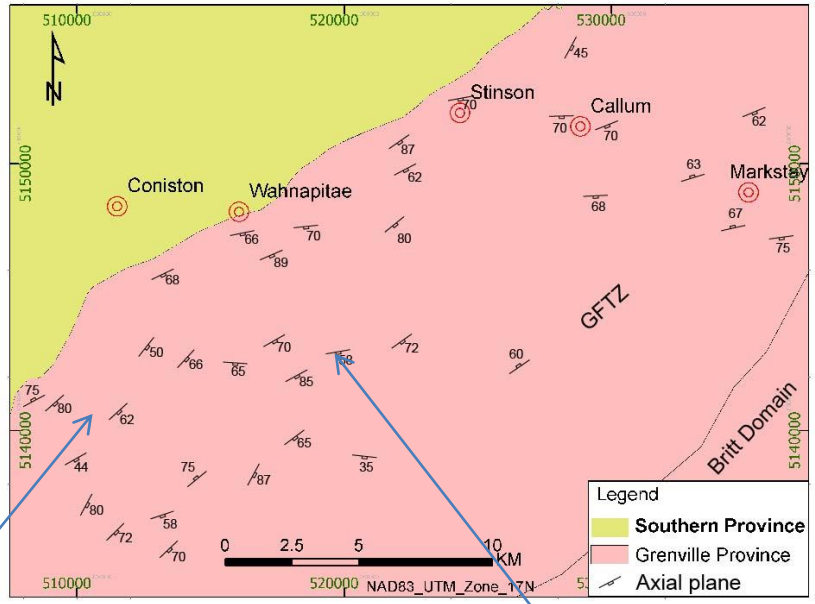

Style?

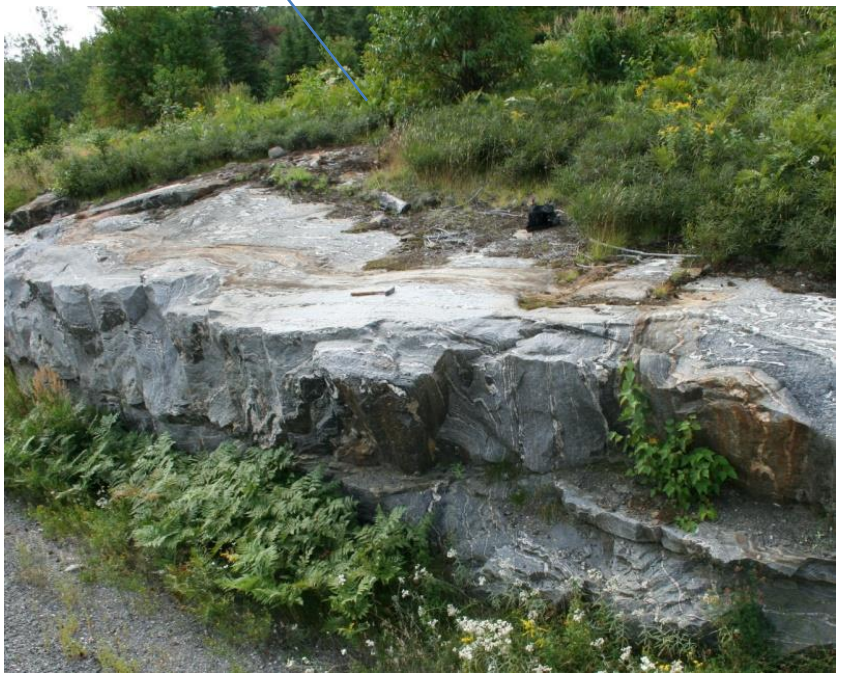
Orientation?

Overprinting?

Generation?

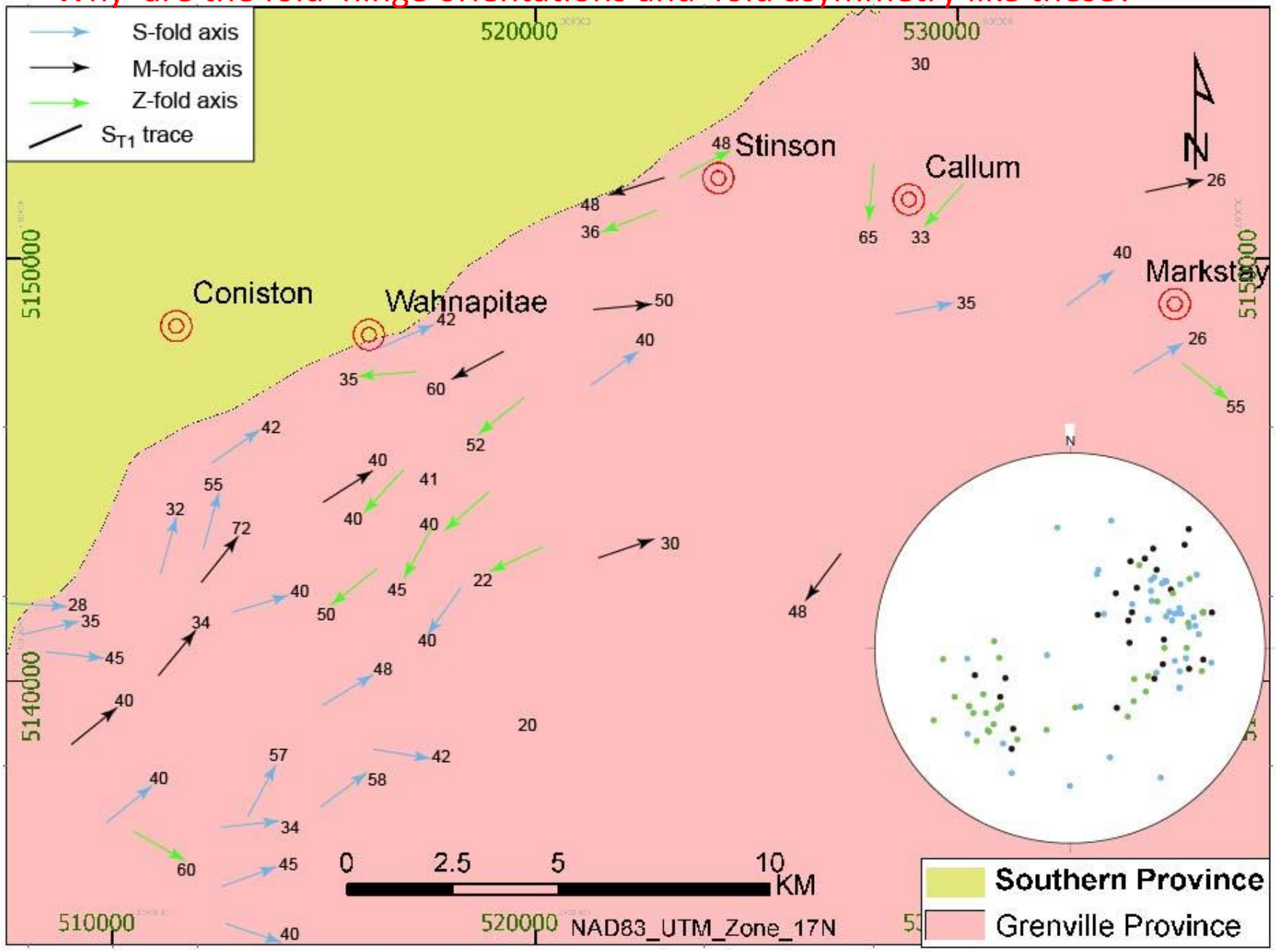
Same as previous one?

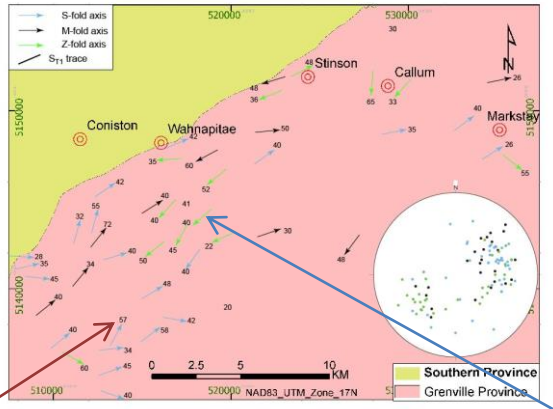


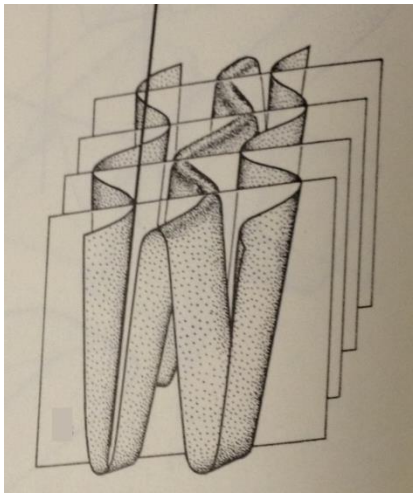



ENE-striking axial plane  Fold hinge plunges toward……

Why are the fold hinge orientations and fold asymmetry like these?





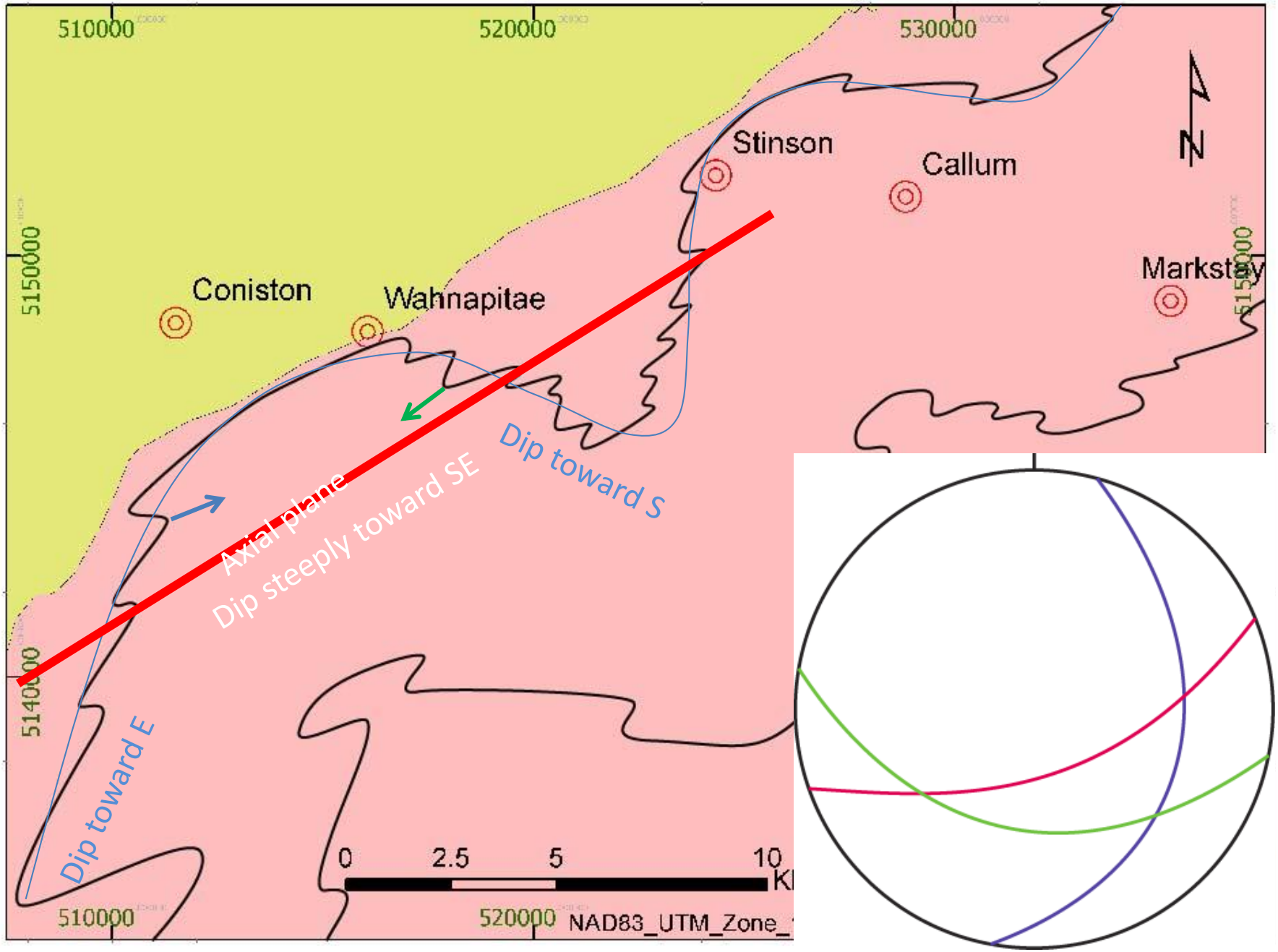



Long limb: strikes E-W, dips steeply toward S

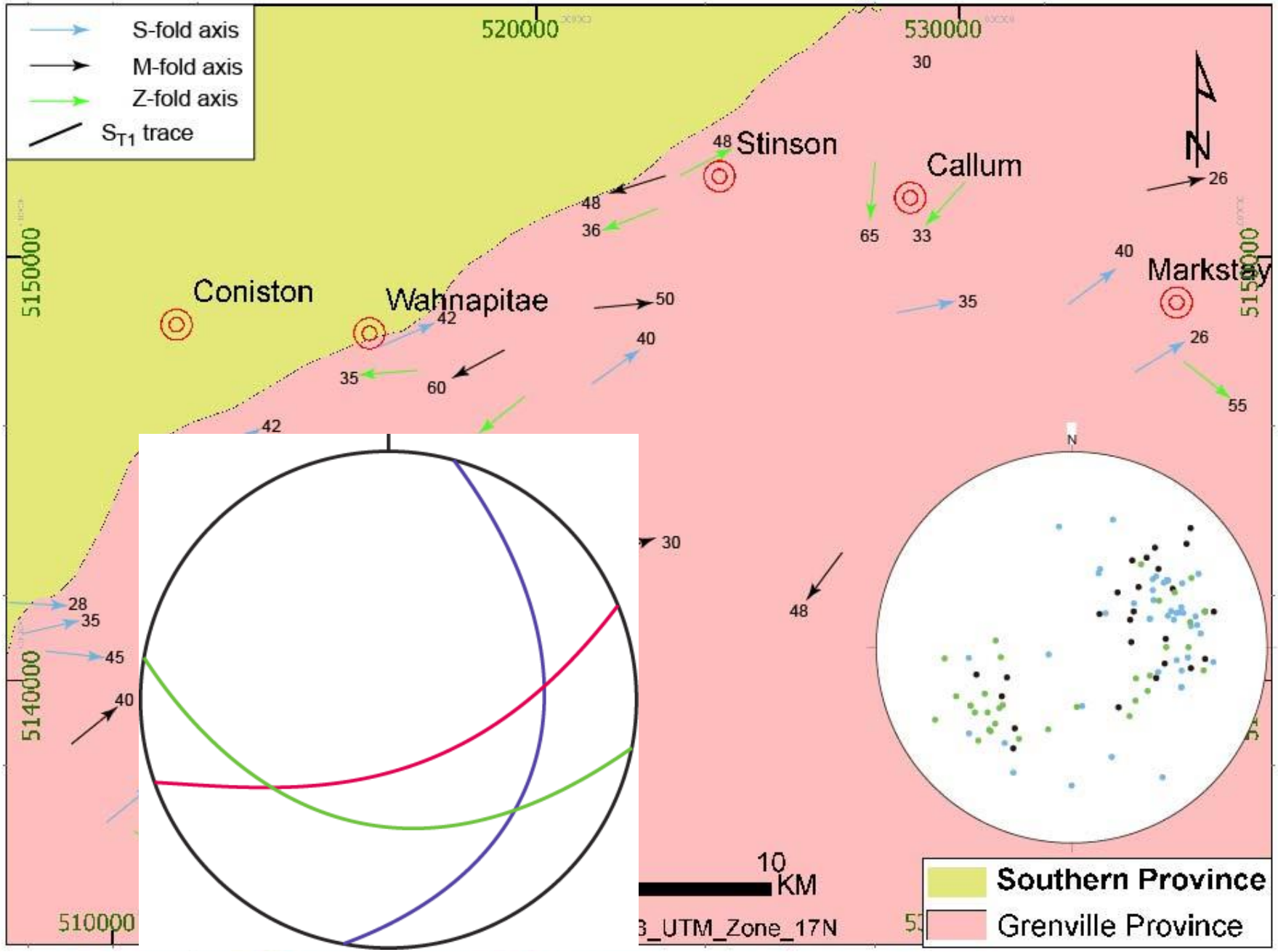
Fold hinge line: intersection of axial plane and enveloping surface

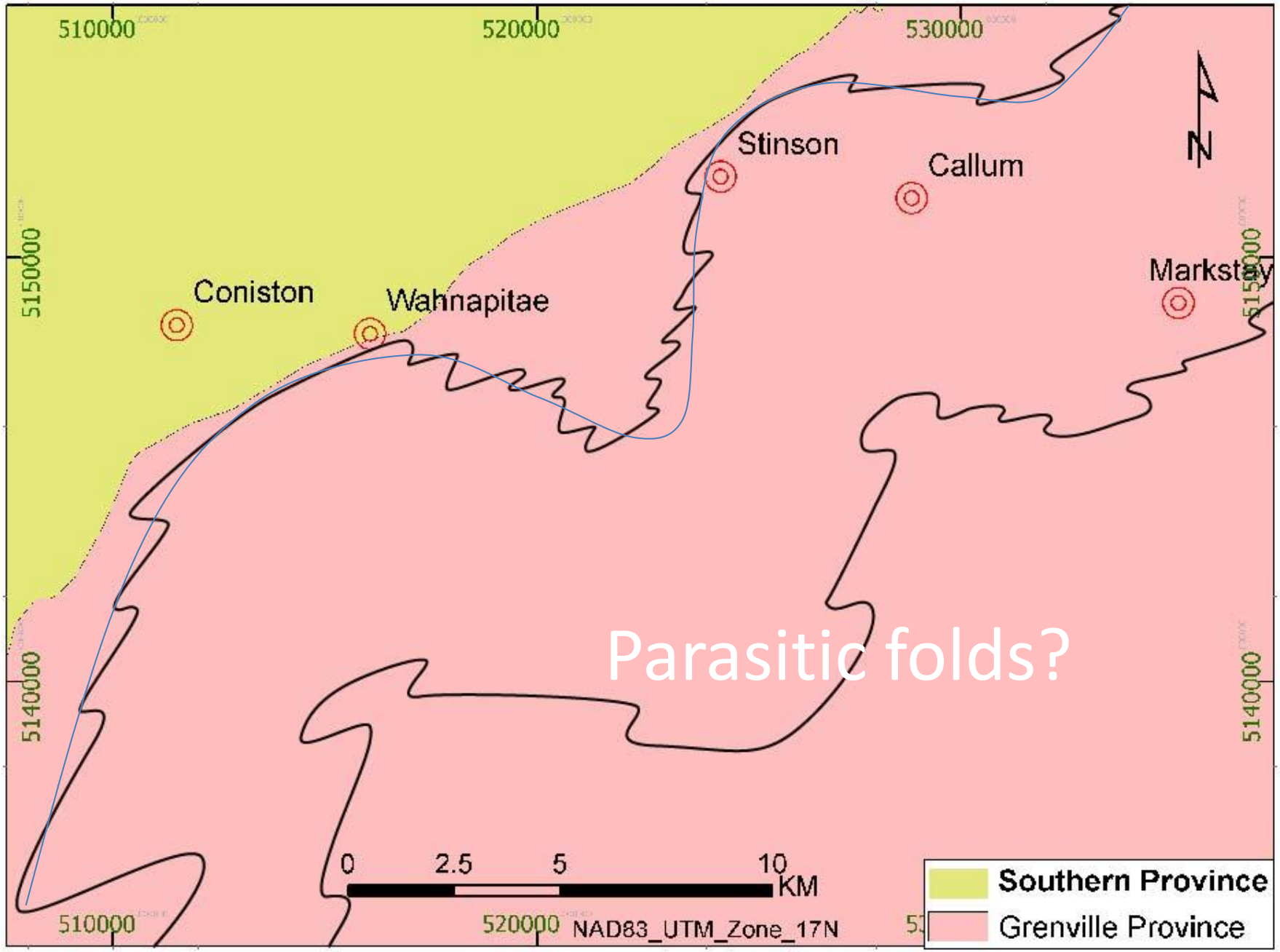
Long limb: strikes 040, dips toward SE

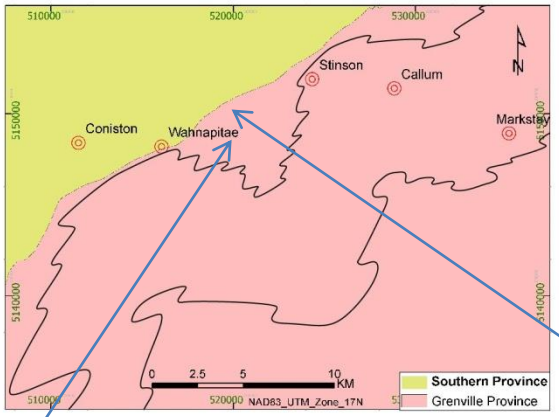
axial planes strike ENE and dip steeply toward SE


510000
520000
530000
5150000
5140000
Stinson
Callum
Markstay
Coniston
Wahnapitae
N
Axial plane
Dip steeply toward SE
Dip toward S
Dip toward E
0
2.5
5
10
510000
520000
NAD83_UTM_Zone_

# Why are the fold hinge orientations and fold asymmetry like these?




510000
520000
530000
5150000
5140000
Stinson
Callum
Coniston
Wahnapitae
Markstay
N
Parasitic folds?
0
2.5
5
10
KM
NAD83_UTM_Zone_17N
Southern Province
Grenville Province



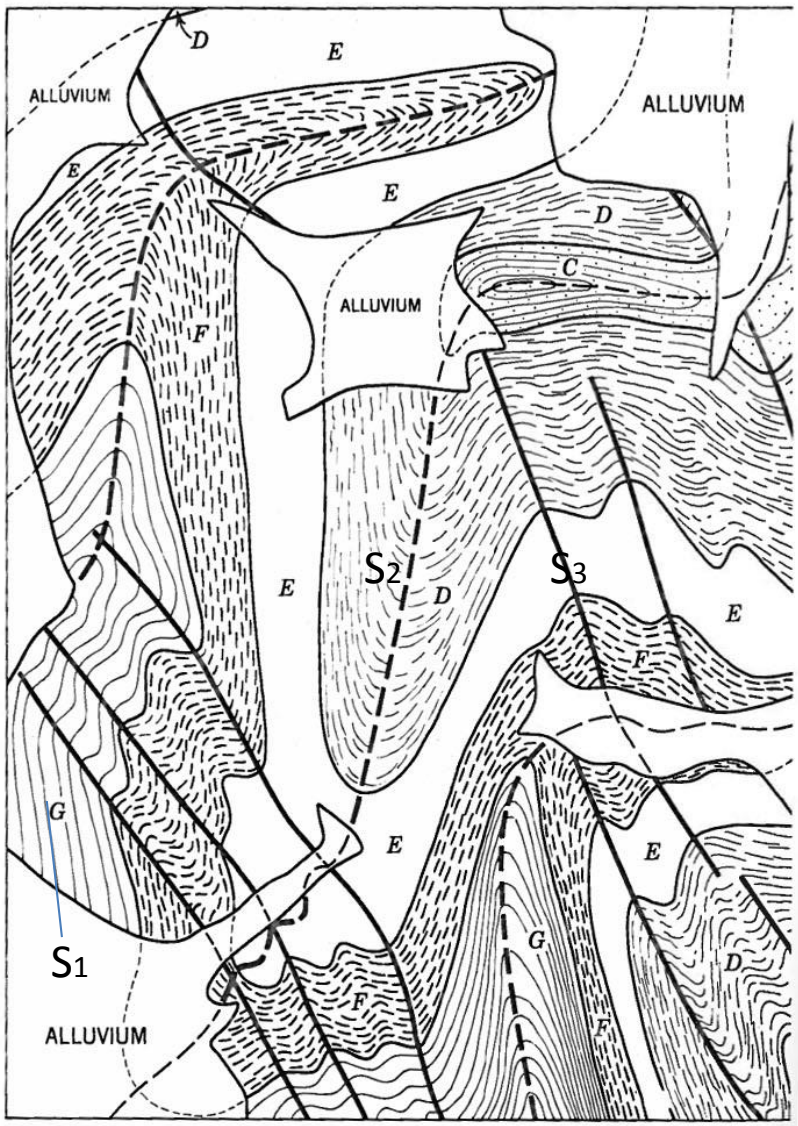

Isoclinal fold in the high-strain zone

Toward NW, inter-limb angle decreases.

What is the generation of this fold?

# Analysis using equal-area projection

## One example



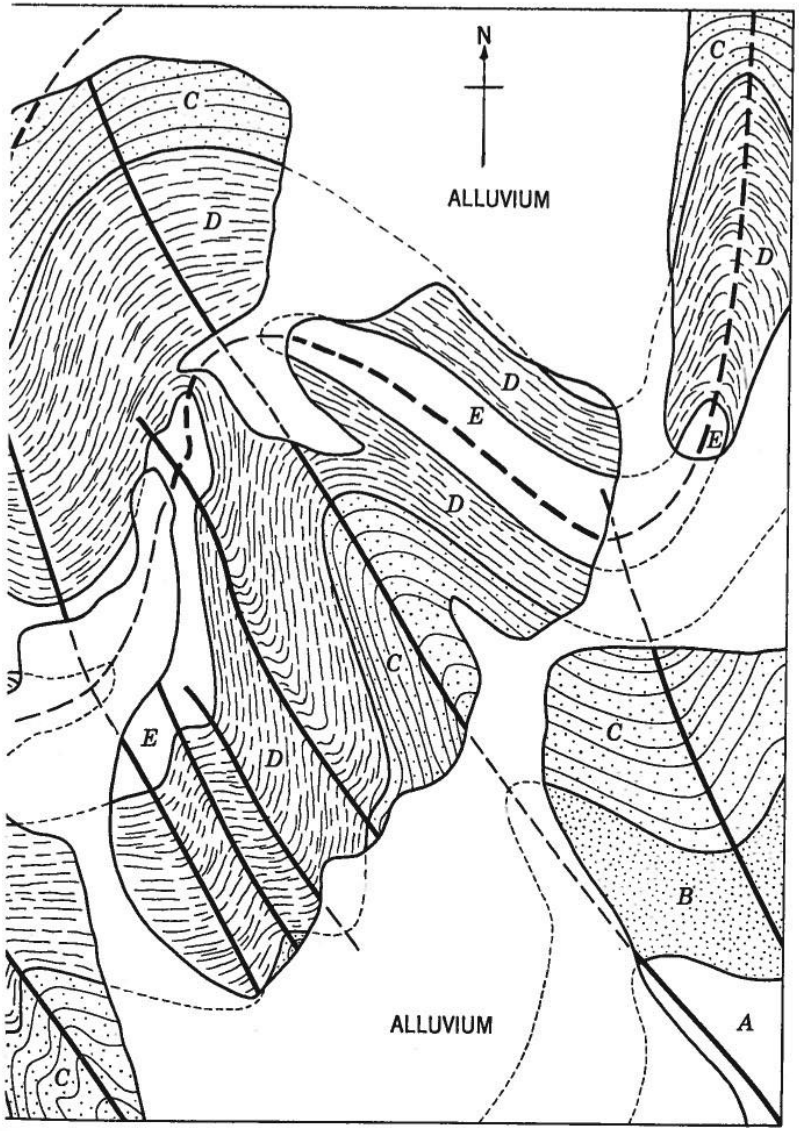




FIG. 5-23. Diagrammatic map of body containing superposed folds in a lithologic lines, traces of axial surfaces of second generation $S_3$. A, B,.....,E are mappable layering $S_1$. Broken lines, traces of axial surfaces of first generation $S_2$; full dark lithologic units.

From textbook Turner and Weiss, 1963. Structural analysis of Metamorphic Tectonites. Page 176

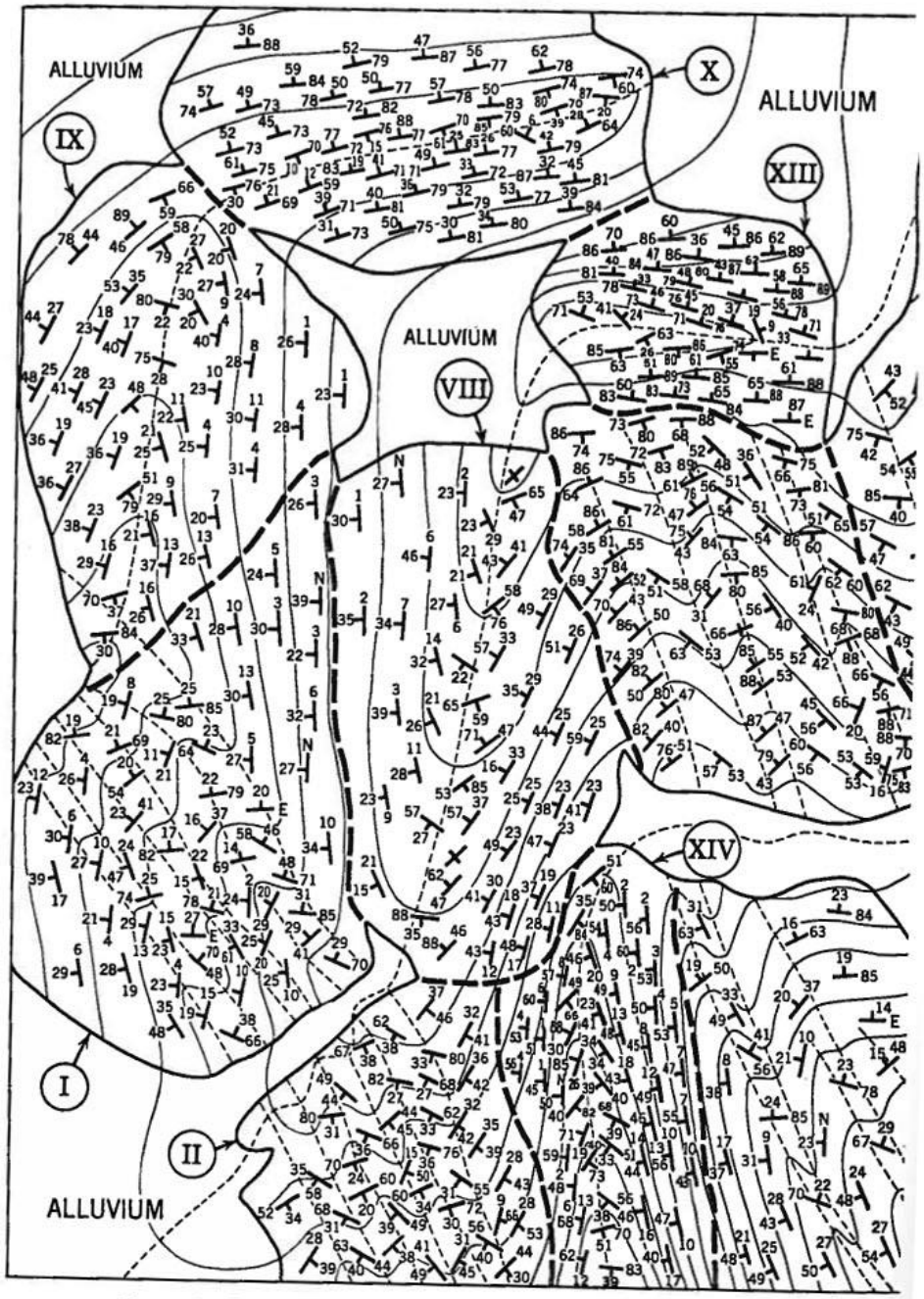



FIG. 5-24. Domains of plane cylindrical folding of $S_1$ with $S_3$ as axial plane (I to VII) and with $S_2$ as axial plane (VIII to XIV) (from Fig. 5-23).

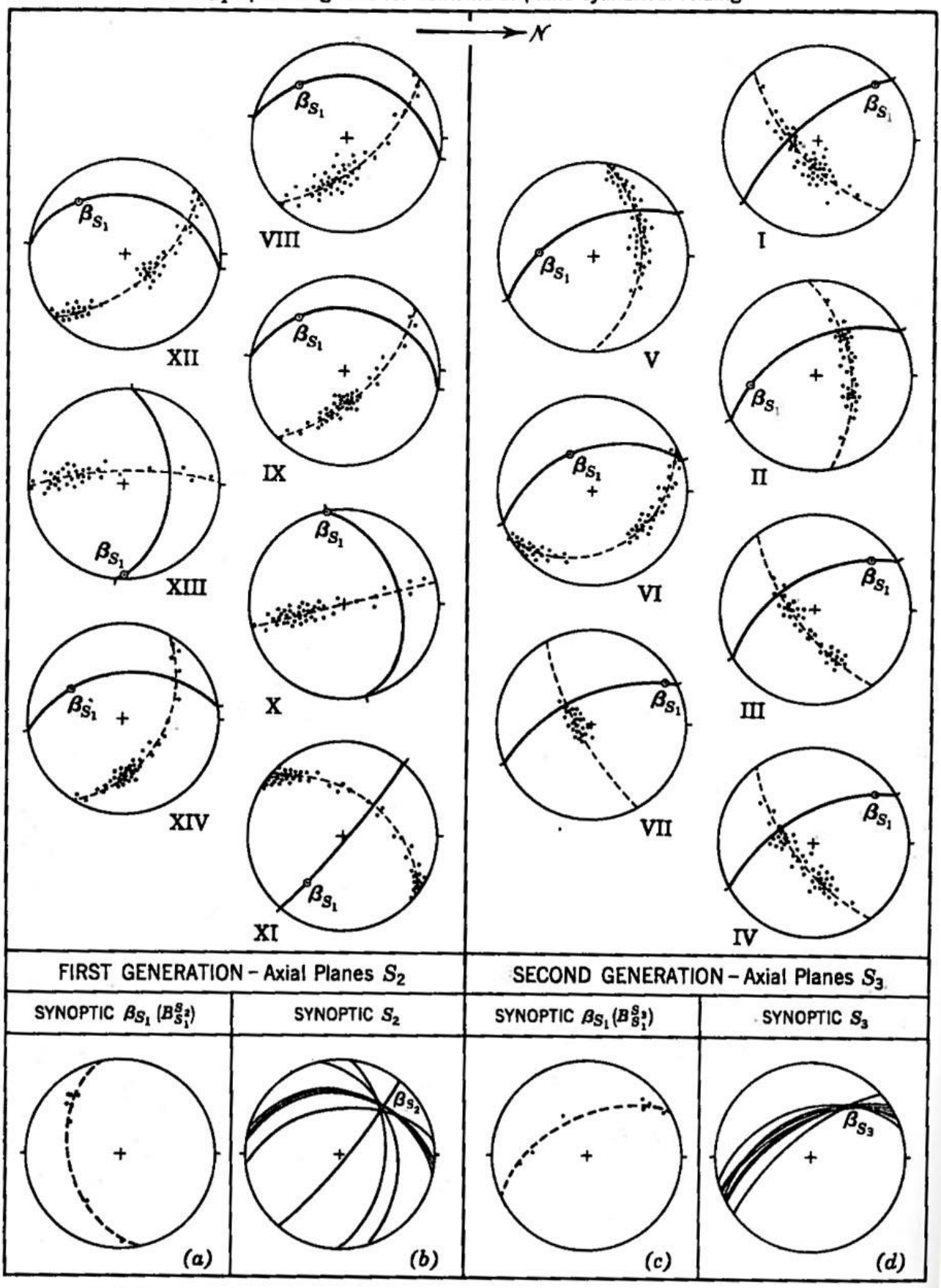



FIG. 5-25. Projections of data from Fig. 5-24 (explanation in text).